Oceanus

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Ocean Observatories

Continuous Access to the Depths, New Heights of Earth Knowledge

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Ocean Observatories

COVER: *Components of a seafloor ocean observatory form the backdrop for a concept of a second-generation model of WHOI's Autonomous Benthic Explorer (ABE). Such autonomous underwater vehicles will play important roles in ocean observatories, with the capacity to upload power and download data from underwater observatory docking stations. ABE's principal designers are Dana Yoerger, Associate Scientist in the Deep Submergence Laboratory; Albert Bradley, Principal Engineer in the Applied Ocean Physics and Engineering Department; and Barrie Walden, Principal Engineer and Manager of Operational Science Services. The National Science Foundation funds their research. Illustration by E. Paul Oberlander*

Atlantis

Alvin

ABE II (artist's concept)

A Sea Change in Ocean Science

When new technology expands our ability to explore the oceans, we take quantum leaps in understanding our planet.

After World War II, new instruments aboard dedicated oceanographic ships revealed the seafloor as anything but featureless and static. The late-1960s plate tectonics revolution provided a new dynamic framework for understanding fundamental Earth processes that spawn earthquakes, build mountains, and create volcanoes, mid-ocean ridges, islands, undersea oil reservoirs, and other geologic features.

A decade later, new emphasis on deep-sea technology brought the discovery of previously unimagined oases of life at mid-ocean ridge hydrothermal vents.

Such discoveries provide convincing evidence that Earth's oceans, atmosphere, life, and the solid planet itself are all interrelated and that Earth constantly changes even as we try to understand it.

Imagine an extraterrestrial exploratory vehicle landing in a Vermont forest in February. Five days of zealous data-gathering might lead to the quite logical conclusion that an unknown phenomenon caused a rapid climate change that turned Earth into a cold, barren planet. We know the phenomenon as winter.

The lesson is that we must go beyond taking intermittent, isolated snapshots of the ocean. We need to know not only what's there, but also what's *going on* there. We must begin to monitor the dynamic, complex, intertwining Earth processes that unfold over long time periods and large areas and to capture important oceanic events that happen in an instant or in previously overlooked places. We need to establish a global, long-term *presence* in the oceans—a vast, hostile, hard-to-penetrate, extraterrestrial environment for humans.

Fortunately, the teaming of scientists and engineers makes this possible. As you will read in these pages, they are harnessing technological advances to create a revolutionary new way to conduct ocean research: ocean observatories. We are on the brink of the next era of major oceanographic discovery.

In an age when rapidly burgeoning human population imposes ever-mounting environmental stresses on our planet, ocean observatories will help us unravel Earth processes that have enormous societal impacts, including hurricanes, tsunamis, earthquakes, beach erosion, toxic algal blooms, declining fisheries, and coastal pollution. They will allow us to grasp the ocean's role in shaping our climate and give us the potential to predict short-term climate changes that spawn floods, droughts, heat waves, mudslides, and even weather- and water-related epidemics such as cholera and malaria. Ocean observatories are a window onto a huge, previously inaccessible, and hitherto unknown biosphere that may have biomedical and industrial potential, and that may teach us about the origin of life on Earth and elsewhere in the solar system.

I believe the oceans are key to sustaining life, and the quality of life, on this planet. The future is now, and it comes just in time.

—Bob Gagosian, WHOI Director

Bob Gagosian

Seeding the Oceans with Observatories

In the midst of the vast ocean, a moored observatory does its work, continually taking measurements to track oceanic and air-sea processes that influence Earth's climate.

Taking the next strategic steps to explore the Dynamics of Earth and Ocean Systems (DEOS)

Keir Becker Professor, Rosenstiel School of Marine and Atmospheric Science, University of Miami
and the DEOS Steering Committee*

Ship-borne expeditions have been the dominant means of exploring the oceans in the 20th century. Scientists aboard ships made the observations and gathered the data that confirmed the revolutionary theory of plate tectonics, which demonstrated that the earth is a complex, multi-faceted system that changes over time. But that revelation also exposed a major shortcoming of the ship-based exploratory approach: its very limited ability to quantify change.

Geoscientists now realize that the earth is dynamic. It cannot be studied adequately in a static manner by simply examining limited regions for short periods. Traditional mapping and sampling strategies provide only infrequent, intermittent snapshots of myriad, ongoing, interlinked, global processes that actively shape the earth and have impacts on society.

Consider these three examples:

- El Niño events, especially in 1982–1983 and 1997–1998, clearly demonstrated the profound societal impacts of dynamic earth and ocean processes and the importance of understanding their behavior.
- Over the past two decades, geoscientists have discovered entirely new ecosystems around hydrothermal vents,

Seafloor observatories, like this one conceived for the NEPTUNE project, could host an array of sensors and serve as a base for robotic exploration.

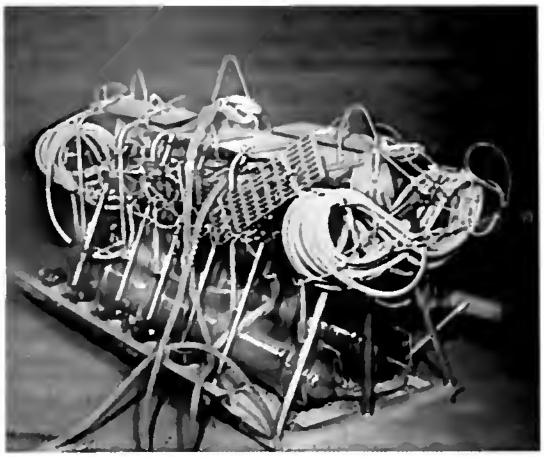
*Members of the DEOS Steering Committee: **Keir Becker**, University of Miami (co-chair); **Alan Chave**, WHOI (co-chair); **John Baross**, University of Washington; **Bobb Carson**, Lehigh University; **John Delaney**, University of Washington; **Robert Detrick**, WHOI; **Tim Dixon**, University of Miami; **Fred Duennebier**, University of Hawaii; **Adam Dziewonski**, Harvard University; **Chuck Fisher**, Pennsylvania State University; **Chuck Nittrouer**, University of Washington; **John Orcutt**, Scripps Institution of Oceanography; **Adam Schultz**, Cambridge University.

whose existence is linked to ongoing or episodic volcanic and magmatic processes on and below the seafloor near mid-ocean ridges. The vents have generated exciting new lines of inquiry about the origin of life on Earth and the possibility of life on other planetary bodies that are similarly endowed with water and volcanism.

• Less well-known but certainly equally complex processes occur at subduction zones, where old seafloor sinks back into the mantle. These processes occur on scales of tens to thousands of kilometers over months to hundreds of millions of years, yet they generate catastrophic earthquakes and tsunamis that occur in seconds over small areas around the Pacific "Rim of Fire," for example. Subduction processes also play an important role in recycling chemicals to the mantle, and they are a primary cause of tectonic uplift and mountain- and island-building on Earth.

To fully understand the causes and effects of all these phenomena, we need a much better grasp of Earth's complex, dynamic processes before, as, and after they occur. This will entail a significant philosophical and cultural change in the way we conduct our science. It will require a coordinated investment in a new mode of marine geoscience investigations: the establishment of long-term ocean observatories. Such observatories offer an essential means to observe interrelated processes over time and to fill in the rather extensive gaps in remote ocean regions where data on deep Earth structures and properties have never been collected.

While scientists have maintained observatories on land for centuries, the practice has not yet received broad support in the oceans. But many national deep-water geoscience initiatives have recently embraced strategies involving seafloor observatories to investigate the earth, including the Ridge Inter-Disciplinary Global Experiments (RIDGE), the MARGINS study of rifted and convergent plate boundaries, the Ocean Seismic Network (OSN), and efforts with the eponymous names BOREHOLE and CABLE, which seek to take advantage of Ocean Drilling Program (ODP) boreholes and submarine cables for geosciences research. Since 1997, scientists involved in these initiatives have joined in a planning effort supported by the National Science Foundation to lay the groundwork for a proposed long-term observatory program called Dynamics of Earth and Ocean Systems (DEOS). And this philosophy is also being embraced in other disciplines of ocean sciences, as well as internationally, so there is an unprecedented opportunity and need for cross-disciplinary, multi-national coordination of scientific objectives and infrastructure.



The Hawaii-2 Observatory, the first long-term, mid-ocean seafloor observatory, was deployed in 1998, taking advantage of a retired trans-Pacific telephone cable.

Observing dynamic global processes

Current and planned seafloor observatory efforts come in two flavors:

1) "Active Process" observatories are located where particular Earth systems are presently most active near the surface. Many of the best examples are at plate boundaries: at mid-ocean ridges, the settings of possibly the most complex interplay among tectonic, magmatic, hydrothermal, and biological processes on Earth, and at subduction zones, where tectonic and magmatic processes have great destructive impact on society. Because these plate tectonic boundaries occur almost exclusively beneath the seas, a seafloor observatory capability is imperative on both scientific and societal grounds.

2) "Global Imaging" observatories would provide "blanket" data coverage of the earth, collecting data from all the necessary places and angles to give us a "big-picture" perspective of our planet. Such a global network of observatories would allow us to fully image the interior of the earth and to provide a comprehensive view of processes that occur over very long time scales and over the entire globe. With 70 percent of the earth's surface under the oceans, global networks will never be complete without seafloor observatories.

Because these obser-

William Birkemeier

Scientists at the Field Research Facility in Duck, North Carolina, use the Coastal Research Amphibious Buggy (CRAB) to deploy instruments for studies of the dynamic processes that shape beaches.

George Tupper

A prototype Argo float is tested in the Labrador Sea. Scientists hope to seed the oceans with 3,000 similar floats to measure oceanic conditions and transmit data to shore via satellite.

vatories open windows onto Earth processes that occur over expanses of both space and time, they are valuable for scientists specializing in many fields. Consequently, observatory networks can be located, configured, and used for multi-disciplinary studies to maximize the investment required to establish them.

Although individual seafloor observatories may have different primary scientific goals, they share many common technological needs. To deploy and maintain long-term monitoring equipment in the remote and hostile seafloor environment, scientists will have to address several requirements. They will need to deliver long-term power to seafloor instruments, a link for data transmission from the seafloor to land (preferably in near real time), a means of remote command and control of seafloor instruments, and ways to facilitate deployment and retrieval of instruments for repair or refurbishment. Ocean scientists today do not customarily consider these factors. They will have to reorient themselves intellectually and innovate technologically.

A CORK (Circulation Obviation Retrofit Kit) sits in a seafloor borehole, measuring subseafloor fluid circulation processes that may affect earthquakes, ore formation, and subseafloor microbial communities.

Different observatories for different missions

In a series of working group meetings in 1998 and 1999, DEOS developed a strategy to pursue two technologically distinct approaches to implement a national seafloor observatory capability:

• *Observatories linked by submarine cables to land and the Internet.* These include observatories opportunistically deployed, using retired telecommunications cables that may become available in areas of current scientific interest, such as the Hawaii-2 Observatory (H2O). (See article on page 6.) They also include deploying new cables to create observatories in a few selected locations where interesting Earth and ocean processes are most active and near to land. Examples include the Long-term Ecosystem Observatory (LEO-15, page 28), the planned Martha's Vineyard Observatory (page 31), and NEPTUNE, the proposed North East Pacific Time-series Undersea Networked Experiments (page 10).

• *Moored, buoyed observatories that provide power to seafloor instruments and a satellite communication link to land* (see pages 12 and 17). These would require regular servicing and could be deployed in either of two ways: a) for long terms, to complete the distribution of global imaging observatories, or b) for moderate terms (up to a few years) in locations around the world where process-oriented problems can be investigated without a more extensive installation. Examples include experiments to examine processes that generate earthquakes (seismogenesis) in subduction settings, experiments in remote mid-ocean ridge locations, or experiments to investigate circulation and other physical processes that occur in the ocean.

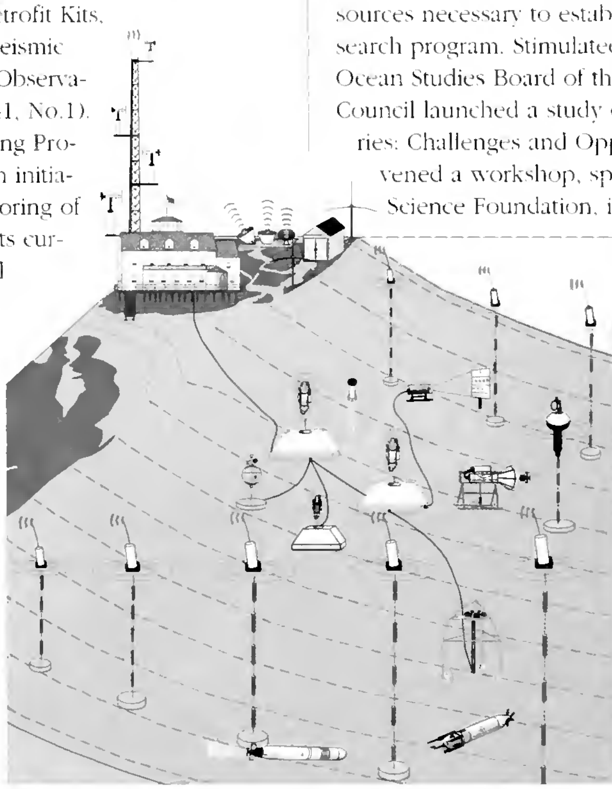
Both buoyed and cabled technologies could be

used for "active-process" observatories. Cabled observatories would be appropriate for long-term installations at selected sites where high amounts of power are needed and large amounts of data are collected. Buoyed observatories would be suitable for shorter-term, less intensive two- to five-year studies. They could be used, for example, to compare processes that occur in hydrothermal vent areas at fast- and slow-spreading ridges, or to study seismogenesis at subduction zones. They would be the principal tool to create a global seismic-wave recording network to "image" Earth's interior (except in the few cases where stations could be accommodated on retired cables).

Coordinating international efforts

Any of the observatory types discussed above—active process and global imaging, cabled and buoyed—may require deploying sensors beneath the seafloor, in the geologic formations where processes actually occur and or where data quality is best. In many cases, DEOS seafloor observatories will include borehole components, such as CORKs (Circulation Obviation Retrofit Kits, page 14), or the Ocean Seismic Network Ocean Bottom Observatory (see *Oceanus*, Vol. 41, No.1). Notably, the Ocean Drilling Program (ODP) highlights an initiative on Long-Term Monitoring of Geological Processes in its current long-range plan, and DEOS has established strong links to ODP.

DEOS goals also strongly mesh with ongoing international initiatives that require coordinated seafloor observatory capabilities. Prime examples include: the International Ridge (InterRidge) initiative for long-term monitoring of the northern Mid-Atlantic Ridge (MOMAR, or MOnitoring the MAR), international MARGINS initiatives to understand seismogenic zones in subduction settings (SEIZE, or SEIsmogenic Zone Experiments), and International Ocean Network (ION) activities to coordinate global network observatory efforts.



Coastal observatories, like LEO-15 in New Jersey, are linked by submarine cable and augmented by robots, radar, and buoyed meteorological sensors

Bringing ocean science to the public & students

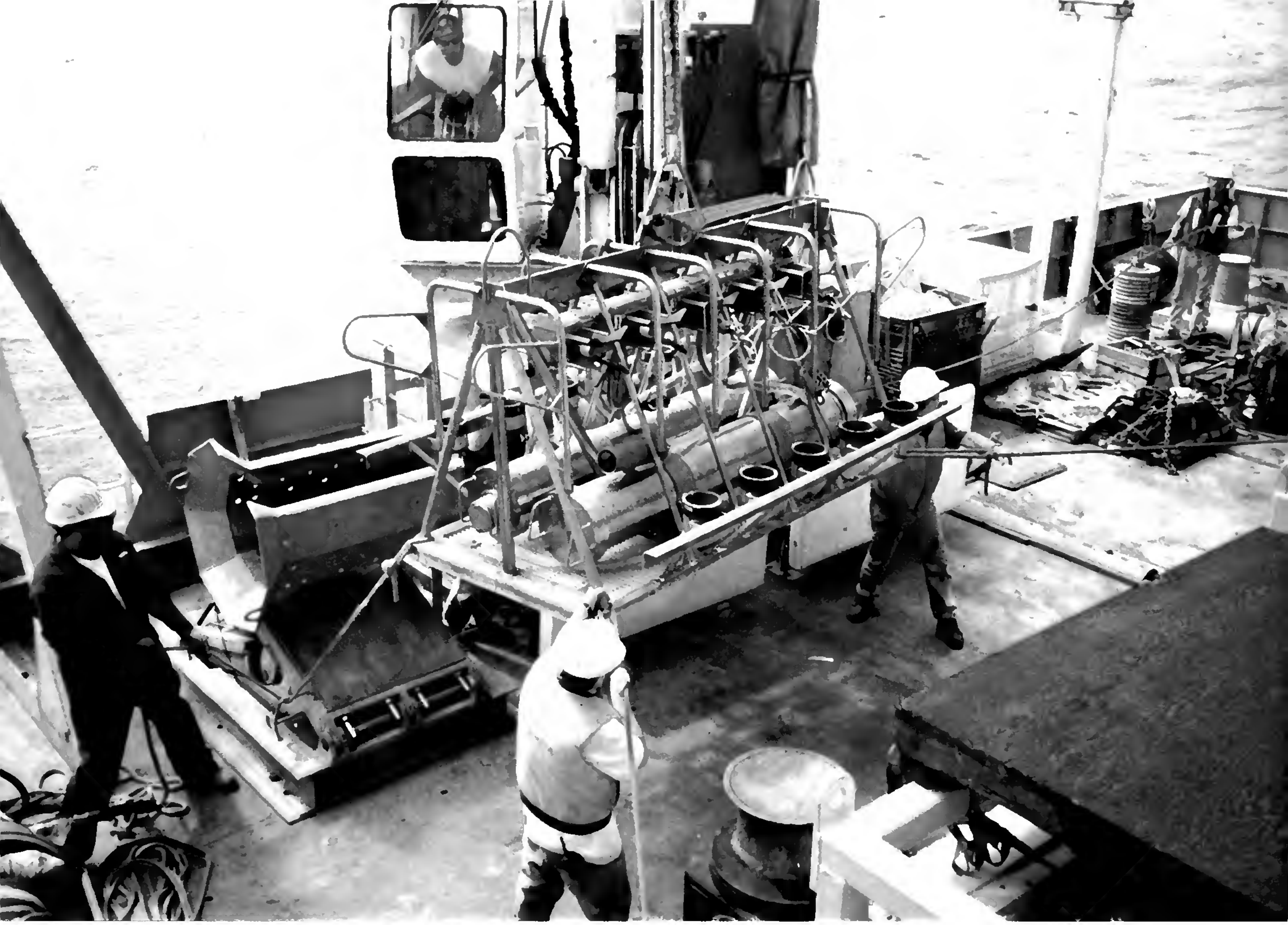
In addition to their scientific value, seafloor observatories with real-time communications capabilities offer an unprecedented opportunity for public outreach and education at all levels. Real-time data links to the deep ocean will allow seafloor instruments to serve as virtual extensions of the Internet and to involve students and the public directly in real science—as it is happening. The public is considerably interested in the remote seafloor in its own right, as well as its potential for learning about life on other planetary bodies. Consequently, DEOS is developing an open data access policy, with plans to devote a significant portion of its budgets to making seafloor data accessible to the public and to educational institutions.

Launching a new observatory initiative

Though DEOS originated in the geoscience community, we eagerly seek to cooperate with all branches of oceanography that share the desire and need to invest in seafloor observatory technologies. In the short term, DEOS aims to achieve broad consensus in the marine geosciences community on the scientific goals and financial resources necessary to establish a formal DEOS research program. Stimulated partly by DEOS, the Ocean Studies Board of the National Research Council launched a study of "Seafloor Observatories: Challenges and Opportunities" and convened a workshop, sponsored by the National Science Foundation, in January 2000, to assess the scientific community's interest. With representatives of all fields of ocean and earth sciences, as well as planetary exploration, we hope to launch the short- and long-term scientific and technological planning that will be required, at both national and international levels, to create a pioneering research program with lasting scientific impact. We believe that ocean observatories are an essential and exciting next step that will allow us to make a scientific quantum leap akin to the plate tectonics revolution. By gaining access to the depths, we can bring understanding of our planet to new heights.

Further information on DEOS, its working group reports, and links to its member initiatives can be found on the Internet at: vertigo.rsmas.miami.edu/deos.html

A moored buoy observatory has meteorological sensors above the surface and a string of instruments extending into the deep.



Crew members of the University of Washington's R/V Thomas Thompson *deploy the junction box that provides electrical outlets for scientific instruments at the Hawaii-2 Observatory (H2O), the first long-term, mid-ocean seafloor observatory. The junction box is spliced to a retired submarine telephone cable, which provides power to the instruments and allows data to be transmitted in real time from seafloor to shore.*

Putting H2O in the Ocean

The Hawaii-2 Observatory is the first long-term, mid-ocean seafloor observatory

Alan D. Chave, Senior Scientist, Applied Ocean Physics and Engineering Department, WHOI
Fred K. Duennebier, Professor of Geophysics, University of Hawaii
Rhett Butler, Program Manager of Global Seismographic Network, Incorporated Research Institutions for Seismology

A major obstacle impeding our ability to understand many of the earth's fundamental, ongoing dynamics—quite frankly—has been a dearth of electrical outlets and phone jacks on the seafloor.

On land, scientists have long been able to plug in instruments to take long-term measurements of earthquakes, variations in Earth's magnetic field, and other episodic or continual geophysical processes. However, deploying instruments in the ocean, and on and below the seafloor, presents unique challenges. First, expeditions to remote ocean regions are more expensive and time-consuming, and they depend on the limited availability of ships. Marine scientists also must contend with corrosion problems peculiar to ocean environments. And without those oceanic outlets and phone jacks, scientists have had limited capacities to supply power to instruments and to store data recorded by them out in the middle of the ocean.

As a result, the record of land-based measurements contrasts starkly with the near-total absence of long-term geophysical data from the seafloor. Since the earth is mostly covered by ocean, that has

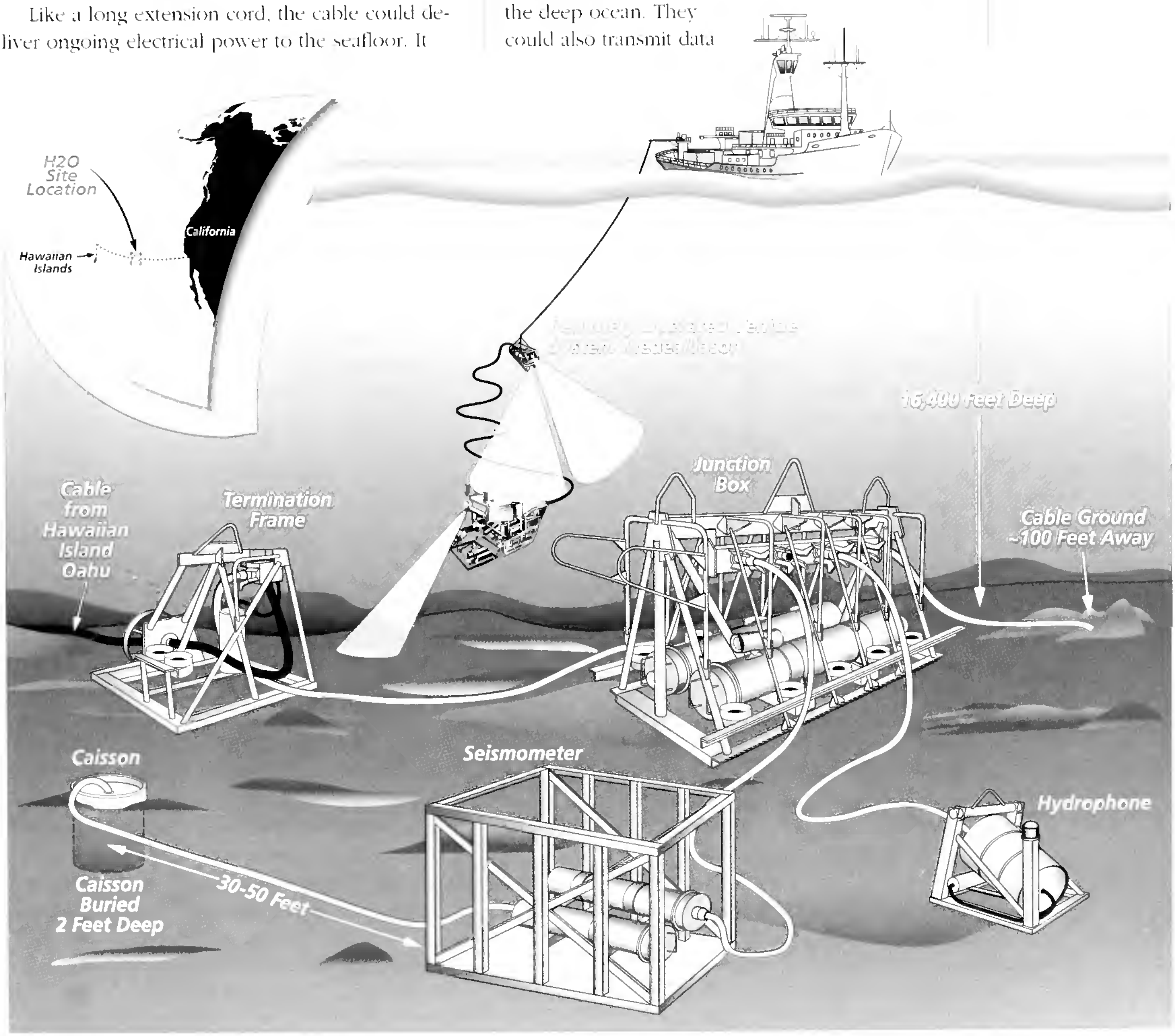
been like trying to monitor the dynamics of a household, for example, by observing events in only the living room and one bedroom.

But in 1998, we seized an opportunity and took a long-sought, significant first step toward opening the relatively unexplored submerged regions of our own planet to more thorough examination. Beneath 5,000 meters of water midway between Hawaii and California, a submarine telephone cable called HAW-2 (Hawaii-2) stretched across the seafloor. Laid by AT&T in 1964, the cable conveyed trans-Pacific telephone calls until 1989, when it broke near California. Moving toward fiber-optic cable technology, AT&T decided not to fix HAW-2 and donated it to the Incorporated Research Institutions for Seismology (IRIS), a consortium of 91 research centers, for the benefit of the scientific community.

Like a long extension cord, the cable could deliver ongoing electrical power to the seafloor. It could also provide a means for two-way, shore-to-seafloor communications to operate instruments remotely and to get data—both in real time. The combination made the retired cable well-suited for a second productive career. In 1995 the National Science Foundation provided funding to develop the technology to take advantage of HAW-2's potential.

Using corrosion-resistant titanium and plastic, we built a junction box to be spliced into one end of the HAW-2 cable. The junction box was designed to provide six simple wet-mateable connectors, into which scientists could plug standard instruments with existing deep-submergence vehicles. No longer constrained by low power, limited internal data recorders, and temporary deployments, the instruments for the first time would be able to take continuous measurements of slowly evolving Earth processes in the deep ocean. They could also transmit data

WHOI Senior Scientist Alan Chave displays a section of the submarine cable that was cut during the installation of H2O. Below, scientists used the remotely operated vehicles Jason *and* Medea *to splice an abandoned submarine telephone cable into a termination frame, which acts as an undersea phone jack. Attached by an umbilical is a junction box, which serves as an electrical outlet for up to six scientific instruments.*



Thomas Thompson *crew members prepare to submerge H2O's first "customer," a package of instruments to record earthquake-generated seismic waves.*

on rapidly occurring events, such as earthquakes, in real time. In 1998, the dream of the world's first long-term, mid-ocean seafloor observatory became a reality, with the establishment of H2O, the Hawaii-2 Observatory.

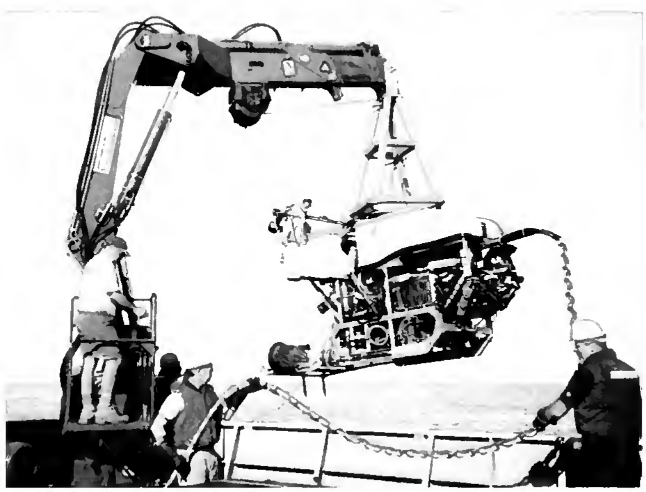
H2O was also in a scientifically ideal site to place a high-priority instrument: a seismometer to record seismic waves generated by earthquakes. Seismologists analyze these waves to locate and study earthquake sources. And—much the way physicians use ultrasound and CT (computerized tomographic) scans to obtain images of tissue inside human bodies—seismologists can also examine seismic waves traveling through Earth's layers to glean information about the structure and properties of rocks in ocean crust, and in Earth's inaccessible mantle, outer core, and inner core.

The key to improving all these studies is getting more high-quality measurements from more angles. But the current Global Seismographic Network (GSN) has been entirely land-based. To provide more global coverage, some seismometers have been placed on islands, but these are not generally representative samples of oceanic crust and, more important, vast areas of the oceans are islandless. Located 2,000 kilometers from the nearest land, H2O is the first of 20 sites identified by the seismological community for an Ocean Seismic Network (OSN) that will fill the wide gaps in the GSN.

Located at 28°N, 142°W, H2O substantially augments seismic coverage of the eastern Pacific for tomographic studies of the earth. It provides a strategic monitoring point for studies of earthquake sources in the United States' most earthquake-susceptible regions: California, the Pacific Northwest, Alaska, and Hawaii. With H2O seismic data transmitted via the submarine cable to Hawaii in real time and available immediately via the IRIS Data Management System, seismologists can precisely locate earthquake sources within tens of minutes after a seismic event.

H2O also has a deep-water pressure gauge to aid research on tsunamis, large waves generated by earthquakes in the open ocean. Tsunamis caused by earthquakes from the Gulf of Alaska to Central America can be recorded at H2O 30 minutes to two hours before they arrive in the Hawaiian Islands, so H2O eventually may be incorporated into tsunami warning networks.

H2O's enhanced global coverage also offers an advantage for studies of another global phenomenon—geomagnetism. Its power and communications capacities open up new opportunities for creative approaches by physical oceanographers, marine biologists, and other marine scientists.



ROV Jason *is deployed to plug instruments into the Hawaii-2 Observatory on the seafloor.*

Anticipating that H2O would be a prototype for future seafloor observatories, we aimed to make H2O as simple and cost-effective as possible to use and deploy. An initial requirement was designing a seafloor system that could be installed using a conventional oceanographic ship, rather than a specialized cable ship.

In September 1998, aboard the University of Washington's R/V *Thomas Thompson*, a survey

showed that the proposed site to install H2O was clear of rock outcrops and other topographic complications and well-suited for an observatory. *Jason*, the remotely operated vehicle (ROV) operated by WHOI's Deep Submergence Laboratory, was deployed to find the 1¼-inch-wide cable on the seafloor. *Jason* followed the cable for 5,000 meters (one water depth from ship to seafloor) toward California and severed it using a special hydraulic cable cutter. This was done so that equal lengths of cable would hang from either side of an 800-pound grapnel lowered from the ship to snag and retrieve the cable—just the way you would pick up and balance a strand of spaghetti on a fork tine. Six miles of cable dragged through water put a load on the ship's wire and winch that approached their working limit of 24,000 pounds, and retrieval took nearly a day. Personnel from WHOI and Margus Inc., a commercial submarine cable company, accomplished the cable recovery.

Margus personnel spliced the HAW-2 cable to a corrosion-resistant "termination frame," which links via a short cable to the junction box. The system was designed to allow the junction box to be lowered separately to the seafloor during installation and to be retrieved for repair or improvements without the complications of dragging up the cable again.

The system was powered up from an AT&T cable station in Makaha, Hawaii, and for the first time in nine years, HAW-2 was operational.

After several days of testing the system, the termination frame and attached cable were lowered on a trawl wire for deployment on the seafloor—or, at least, that was the plan. The frame was barely over the side when the half-inch chain securing it to the trawl wire snapped, sending cable and frame to the bottom. Expecting the worst, we launched *Jason*'s mechanical teammate, *Medea*, to locate and inspect the damage. Tethered to the ship, *Medea* is a platform that separates *Jason* from the ship motion, allowing the ROV to maneuver more freely. It also has a wide-area camera and lights.

Fortune smiled. The cable was lying in loops 300 meters in diameter, but flat on the seafloor, so that *Jason* could be used without risk of entanglement. At the edge of the coils, the termination was sitting upright, intact, and not embedded in sediments. After powering up the cable, the system was found to be undamaged—though its planned location had abruptly moved about 2 kilometers closer to Hawaii. Installation of the junction box could proceed.

The junction box consists of a protective frame enclosing vulnerable equipment within. The equipment includes a manifold with the eight connectors (one each for the termination frame and a sea ground, and six for scientific instrument packages). The connectors are designed to be plugged in with standard ROV manipulator arms. The frame also encloses two cases designed to withstand deep-sea pressure. One case contains a system developed and built by University of Hawaii engineers to extract and control power from the cable. The other case contains the communication and control system, designed and built by WHOI engineers, that is the heart of the junction box.

The complex system of switches, modems, and computers allows scientists onshore to monitor and adjust individual instruments. It routes signals into and out of individual instruments, ensuring that data streams do not get muddled even though all signals eventually must travel via a common channel through the submarine cable to and from Hawaii. The system is designed with a great deal of redundancy and switching flexibility to keep it operational without making expensive mid-ocean service calls.

Alan Chave

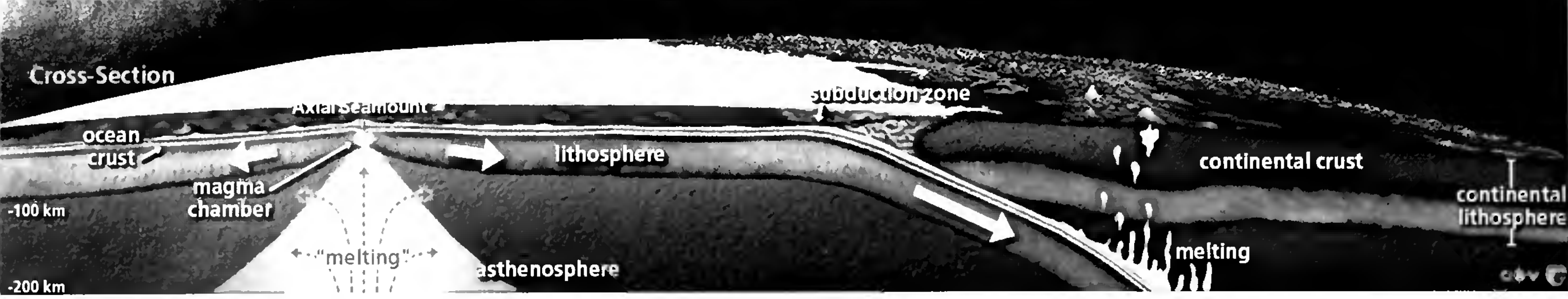
WHOI Research Engineer Bob Petitt designed and built the complex communication and control system that routes signals into and out of individual instruments plugged into H2O. Above, Petitt tests the system with a call from R/V Thompson *through the submarine cable to WHOI Senior Engineer Assistant John Bailey at the cable's terminus, a shore-based station in Makaha, Hawaii.*

The junction box was lowered to the seafloor and *Jason* plugged the system together. The ability to retrieve the junction box separately came in handy immediately when it failed after just 12 hours. It was unplugged and retrieved by *Jason* and *Medea*, repaired aboard *Thompson*, and redeployed and reconnected two days later.

Jason plugged in H2O's first instrument, a multisensor seismo-acoustic package designed and built at the University of Hawaii. Then the ROV buried the seismometer sensor package in a seafloor hole to minimize distorting vibrations from currents. Data began to flow to Makaha, where communications equipment had been modernized and other equipment (salvaged from another retired trans-Pacific cable system from Guam to Japan) was added to provide a mirror image of the H2O junction box on shore.

After H2O had been operating for two months, a water current meter failed and corrupted the seismic data, necessitating a maintenance visit in September 1999. Once again, the system allowed *Jason* to unplug and retrieve the seismometer system for repair and the junction box for an upgrade without touching the main cable itself. The systems were redeployed and plugged in, as before. Four Benthos hydrophones, to measure pressure variations of seismic waves in water, were plugged into another of the junction box's connector ports.

Four more ports are available, and IRIS and NSF welcome interest in deploying new scientific sensors at H2O. Interested parties may contact the authors. Further information may be obtained from the H2O Web site at: www.whoi.edu/science/GG/DSO/H2O/.



NEPTUNE's planned location off the northwest US coast would facilitate studies of various components of Earth's plate tectonic system.

NEPTUNE: A Fiber-Optic 'Telescope' to Inner Space

John R. Delaney, Professor of Oceanography, University of Washington

Alan D. Chave, Senior Scientist, Applied Ocean Physics and Engineering Department, WHOI

It would be a scientific outpost in one of our solar system's most remote and hostile environments. Its mission: to explore the largely unknown fundamental workings of a fascinating planet. Our planet—Earth.

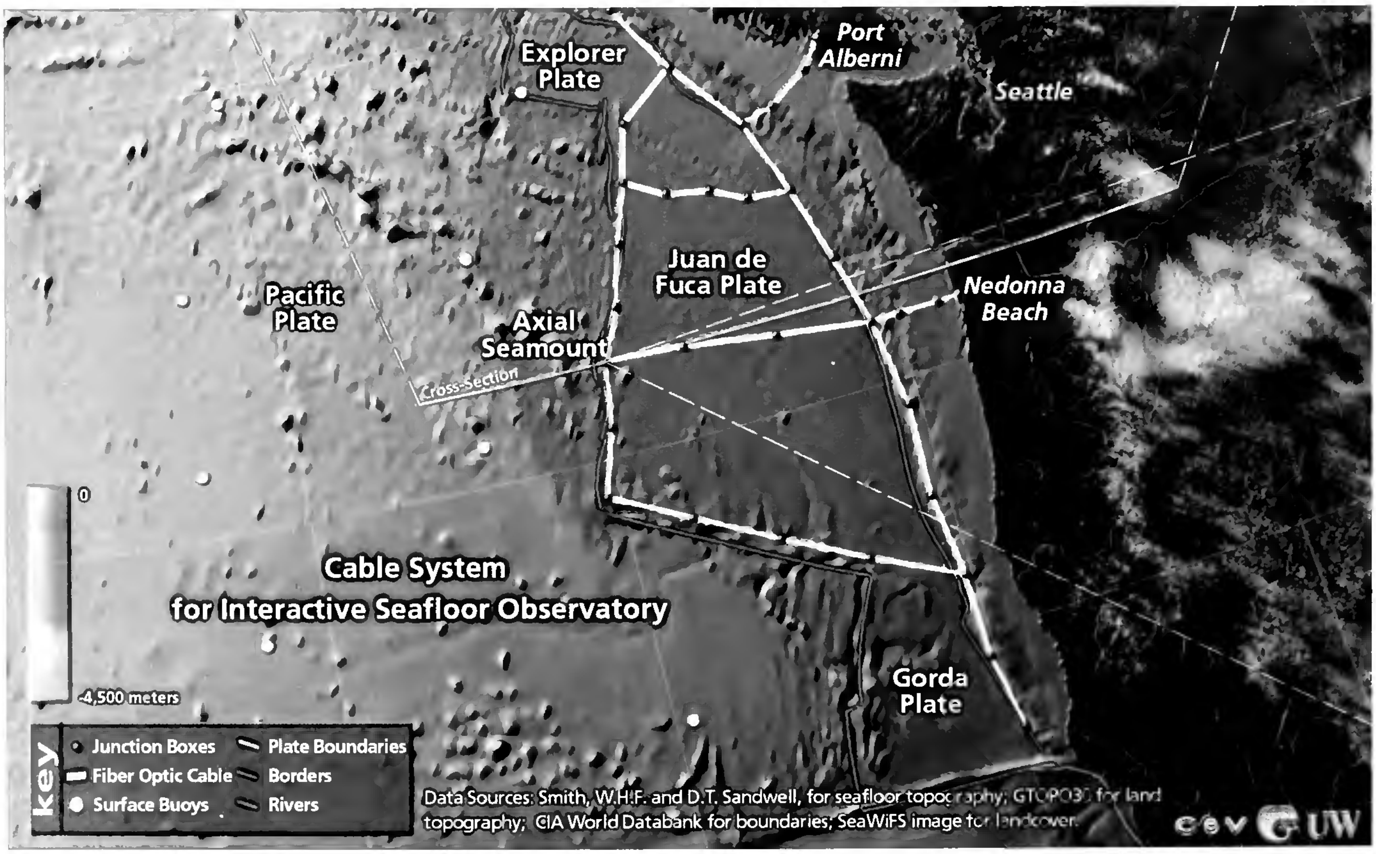
The North East Pacific Time-series Undersea Networked Experiments (NEPTUNE) project aims to establish an extensive earth/ocean observatory throughout and above the Juan de Fuca Plate off the US-Canadian West Coast (below). With it, we can begin to grasp the myriad, interrelated forces and processes that shape our planet and often have societal impacts. Because these processes occur over vast ranges of space and time, and in the ocean, they have remained largely beyond our ability to observe.

To comprehend Earth's dynamic behavior, ocean and earth scientists now realize that we cannot observe small regions for short periods. Snapshots of individual cogs won't give us a good sense of how the whole machine works; we need to see all the interconnected parts, throughout the machine, in action, over a long time.

Advancements in communications, robotic, computer, and sensor technology have made the required next step possible—a long-term presence in the oceans. It will let us examine in detail the complexity of interactions that mold the seafloor, generate earthquakes and volcanoes, form ore and oil deposits, transport sediments, circulate currents, cause climate shifts, affect fish populations, or support life in extreme environments on and below the seafloor.

NEPTUNE is a proposed network of high-speed fiber-optic submarine cables throughout the Juan de Fuca Plate, which encompasses all the major Earth-shaping plate tectonic processes.

NEPTUNE is a proposed system of high-speed fiber-optic submarine cables linking a series of seafloor nodes supporting thousands of assorted mea-



suring instruments, video equipment, and robotic vehicles that could upload power and download data at undersea docks. Unlike conventional telephone cables, which supply power from shore in a straight line, end to end, NEPTUNE would operate like a power grid, distributing power simultaneously and as needed throughout the network. Working much like a campus data network (with nodes analogous to buildings and each instrument like a workstation), NEPTUNE would provide real-time transmission of data and two-way communications.

Bringing the power of the Internet to the seafloor, it would connect submarine experiments directly to scientists in their labs, where they could monitor and adjust instruments or dispatch robots to capture episodic events that now occur unnoticed. NEPTUNE's Internet accessibility also offers intimate, over-the-shoulder views of exploratory science in action that would engage the general public and educate students of all ages.

The Juan de Fuca Plate's proximity to shore and relatively small size make it a cost-effective candidate for incremental but eventually extensive cabling. Yet it encompasses all the major Earth-shaping plate tectonic processes, including submarine volcanism, earthquake activity, hydrothermal venting, seafloor spreading, and subduction. At its coastal edge, instrument arrays also could open new windows onto poorly understood processes that transport sediments from continents to the deep sea, that create energy resources such as oil and gas, or that affect delicately balanced coastal ecosystems.

Oceanographic instruments could shed light on ocean dynamics that affect weather and climate. Still other devices could track the ever-shifting population dynamics and migrations of the Pacific Northwest's great fisheries—offering better management strategies for this crucial, threatened resource.

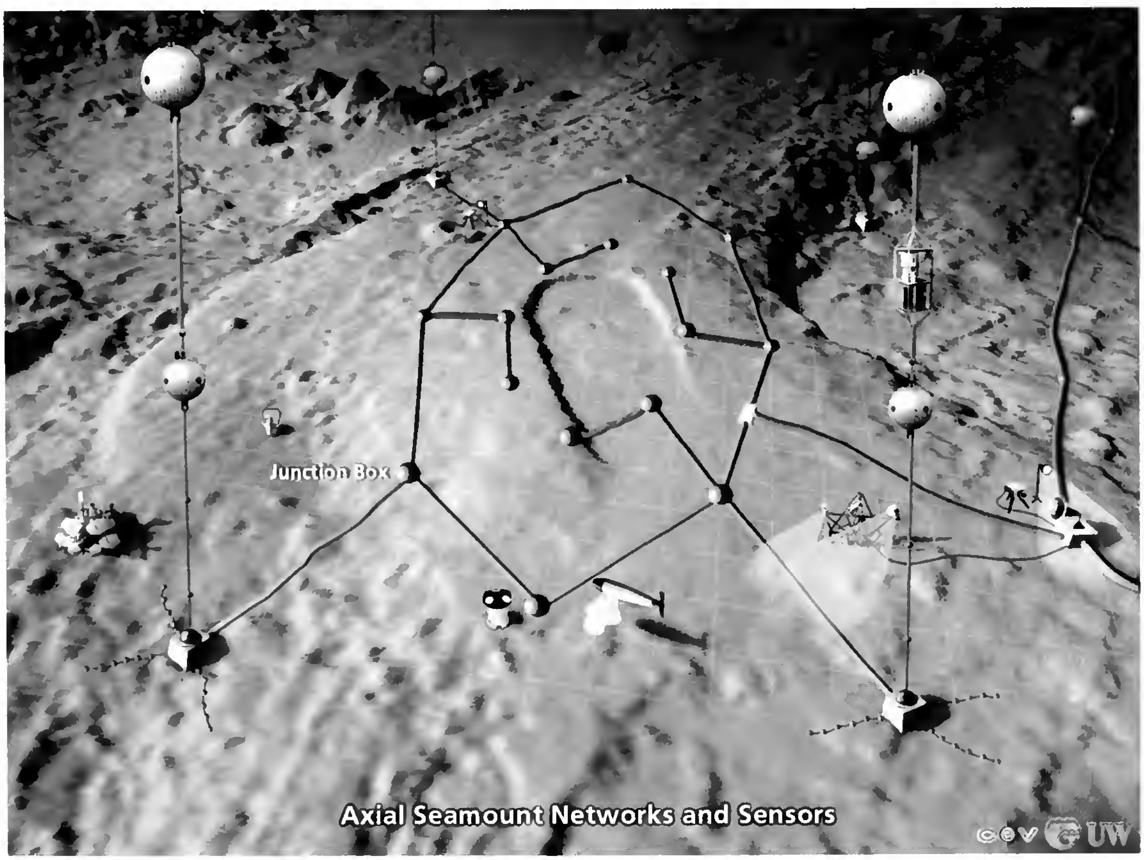
We envision NEPTUNE as a national facility for many types of innovative ocean and planetary investigations that would engage the imaginations of researchers across a spectrum of scientific disciplines. One example—combining geology, chemistry, biology, and oceanography—is the recent discovery that erupting seafloor volcanoes release pulses of chemical nutrients, resulting in "blooms" of microbes that form the base of a submarine food chain. Hydrothermal vents may be "the tips of icebergs" for substantial subseafloor, high-temperature microbial communities, with potential biomedical properties.

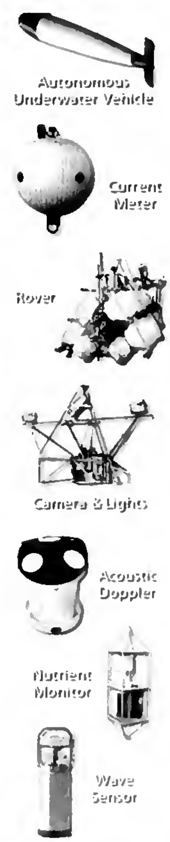
Studies of these microbes offer insights into the origin of life on our planet and the possibility of life on other solar bodies, such as Europa, a moon of Jupiter, where similar submarine volcanic systems may exist. NEPTUNE would drive improvements in deep submergence technology and provide an unparalleled testbed for robotic exploration of extreme environments on other planetary bodies.

For roughly half the $280 million price tag to develop, launch, and operate the Mars Pathfinder mission, NEPTUNE would be a worthy investment in exploration of our own living planet.

Further information is available on the Web at: www.neptune.washington.edu.

The NEPTUNE system would link a series of seafloor nodes supporting thousands of assorted instruments.





Seafloor to Surface to Satellite to Shore

Moored buoys offer potential for continuous, real-time observations anywhere in the ocean

Robert S. Detrick, Senior Scientist, Geology and Geophysics Department, WHOI
John A. Collins, Associate Scientist, Geology and Geophysics Department, WHOI
Daniel E. Frye, Senior Research Specialist, Applied Ocean Physics and Engineering Department, WHOI

The next great leap in our understanding of the earth-ocean system will require us to put our "eyes" and "ears" in the ocean to observe the dynamic processes going on there as they are happening, in real time. In the oceans, physical, chemical, biological, and geological processes are continually interacting—over time scales ranging from seconds to millions of years and on space scales ranging from centimeters to the globe.

A key new tool to untangle these complex interactions will be ocean observatories, with sensors taking measurements in the water column, on the seafloor, and in the earth below. These observatories will require two-way communications capabilities to remotely control instruments and to transmit data in real time back to shore. And they will have to provide power to operate instruments unattended for months or years at a time.

The ability of buoyed bservatories to make long-term neasurements of ngoing processes anywhere in the world's oceans gives them the otential to play an mportant role in ceanographic and climatic studies.

The Dynamics of Earth and Ocean Systems (DEOS) program (see article on page 2) is exploring two technologically distinct approaches for seafloor observatories. The first entails using dedicated cables to link observatories to shore (such as the LEO-15, Martha's Vineyard, H2O, and NEPTUNE projects described elsewhere in this issue). The second involves linking observatories to moored buoys on the ocean surface and transmitting data back to shore via a constellation of Earth-orbiting telecommunications satellites.

Moored ocean buoy observatories have certain advantages. They can be located in very remote ocean areas, far from land, where the cost of laying a fiber-optic cable would be prohibitive. They are also portable and potentially could be used for shorter-term (two- to five-year) studies in one area, and then moved to a new location. This provides greater flexibility, as circumstances change, to reconfigure experiments that track processes continuously over long time periods. It also gives scientists the ability to respond in time to observe transient natural events, or even relocate to a new site, as their knowledge of an area increases incrementally over the course of a study.

Moored buoys, however, have certain limitations. They can't supply as much power to instruments as a fiber-optic cable can, and they can't transmit as much data via satellite. They also require more frequent servicing.

Moored buoy systems have been deployed in the deep ocean since the 1950s as platforms to acquire meteorological and oceanographic data in the upper ocean (see article on page 20), but they have not been used for seafloor observatory studies. So important design questions remain: What is the optimal buoy shape (spar- or disk-shaped floats)? What is the best mooring design (single-point or three-point)? What is the best way to isolate the electromechanical cable connecting the buoy to the seafloor from wave and current motion? How can maintenance costs be curtailed?

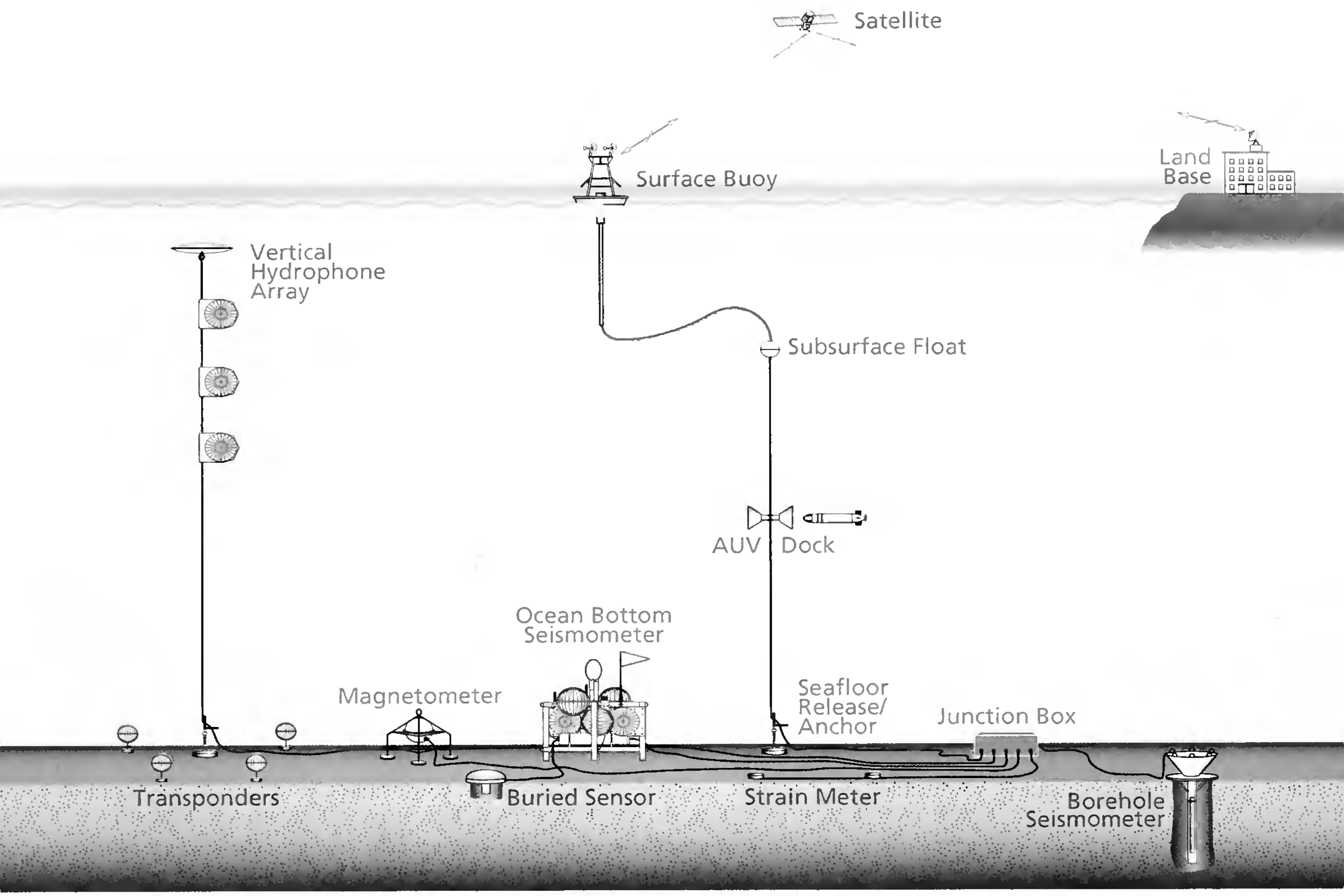
We are currently working with colleagues at the Scripps Institution of Oceanography and the Monterey Bay Aquarium Research Institute, and with a partner from industry, Deep Oil Technology, to design and build a prototype moored ocean buoy seafloor observatory for use in the deep ocean.

One design under study (right) consists of a large (4 to 6 meters in diameter) discus-shaped buoy on a single S-tether mooring, connected to an array of sensors on the seafloor. The S-tether mooring design, developed at WHOI in the early 1990s, combines the advantages of a subsurface mooring (isolation from surface waves and currents, durability and long life, and low cost) with the capabilities of a surface mooring (access to satellite telemetry and a platform for power generation).

It would consist of a surface float, a subsurface float, an "S"-shaped cable connection between the surface and subsurface floats, a standard mooring from the subsurface float to a seafloor anchor, and an on-bottom segment from the mooring to a seafloor junction box.

A variety of sensors (thermistors, flow meters, chemical sensors, seismometers, magnetometers, hydrophones, strain meters) could be plugged into the junction box. The box would transmit power from the surface buoy to these instruments through a double-armored, multi-conductor cable. Data from seafloor sensors would be transmitted up the cable to the surface float for transmission back to shore.

The electromechanical cable would connect to a large subsurface float—a sphere made of buoyant



syntactic material to support the weight of 3,000 meters of cable. A fluid-filled, stretchable rubber hose with an integral coil of electrical conductors would connect the subsurface and surface floats. By carefully distributing flotation along the upper cable section, we can maintain an "S"-shaped tether to effectively isolate the subsurface float from the motion of the surface buoy.

The surface float would be made of a Surlyn foam that is frequently used in marker or navigation buoys in shallow waters. It combines durability, light weight, and low cost. Solar panels, diesel generators, and batteries mounted on the buoy could provide up to 500 watts of continuous power to instruments on the seafloor. An omni-directional antenna atop the buoy would provide bi-directional communication via satellite to shore. We anticipate that a system like this would require annual servicing.

A moored ocean buoy observatory of this design could be used in a variety of experiments requiring long-term observations and real-time data telemetry. For example, a buoy observatory moored over a volcanically active section of the East Pacific Rise or Mid-Atlantic Ridge could monitor all the dynamically interacting volcanic, hydrothermal, and biological processes that occur over two or three years.

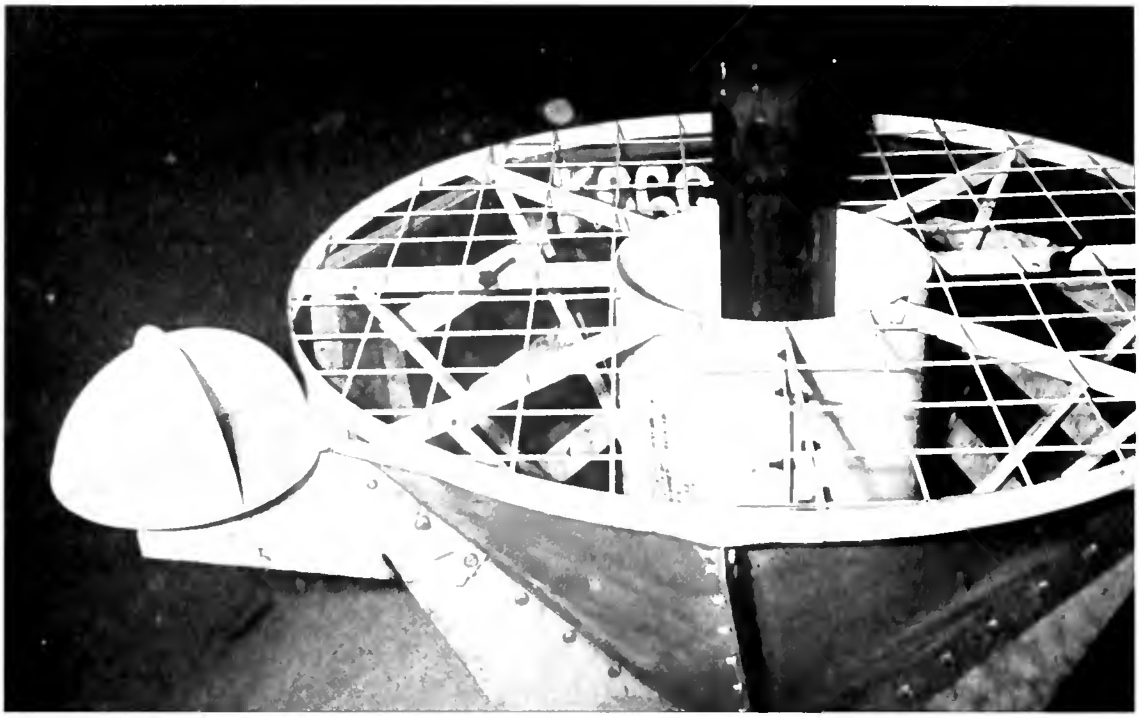
Autonomous underwater vehicles (AUVs) could be stationed at a mooring. On command from shore, these AUVs could resurvey the surrounding area and upload their observations to the buoy for transmission back to shore.

Other buoys could be permanently deployed at some of the 20 strategic (and remote) ocean sites needed to fill large gaps in the global network of broadband seismic stations, greatly enhancing our ability to use seismic waves to image the earth's internal structure. To study processes that generate earthquakes, buoy-based observatory systems linked to an array of seismic and geodetic sensors could be placed in earthquake-prone geological locales—along an ocean transform fault or above a subducting plate landward of an oceanic trench, for example.

The ability of buoyed observatories to make long-term measurements of ongoing processes anywhere in the world's oceans also gives them the potential to play an important role in other oceanographic and climatic studies. They could track the flow of major currents along the oceans' western boundaries or episodic upwelling of water and nutrients at eastern ocean boundaries. They could also be used for experiments using sound waves to monitor ocean temperature changes related to global climate change.

Our research is supported by the National Science Foundation.

In this prototype design for a moored buoy system, a surface buoy connects to an "S"-shaped tether that isolates a subsurface float from surface buoy motions. The surface buoy provides power via a cable to a seafloor junction box that accommodates a variety of sensors. Data from the sensors travel up the cable to the surface buoy for transmission via satellite to shore.



The Ocean Drilling Program's drill ship (left) has deployed several "CORK" observatories in seafloor boreholes to study the circulation of subseafloor fluids (see map below), including the one above in Hole 858G off the Pacific Northwest coast.

Plugging the Seafloor with CORKs

A window into the plumbing system hidden beneath the ocean's floor

Keir Becker, Professor, Rosenstiel School of Marine and Atmospheric Science, University of Miami
Earl E. Davis, Senior Research Geophysicist, Pacific Geoscience Centre, Geological Survey of Canada

Hidden beneath the seafloor throughout most of the world's oceans lies a massive, dynamic plumbing system that is a central component of our planet's inner workings.

Heated and under pressure, seawater and other fluids flow and percolate up, down, and through myriad layers of subseafloor rock formations. At volcanically active mid-ocean ridges, where hot magma rises from the mantle to create new seafloor, this circulation vents heat from the earth's hot interior. It plays an important role in regulating the chemical balance of the oceans and in forming huge ore deposits. At subduction zones, where old seafloor collides with an overriding tectonic plate and sinks back down to the mantle, fluid pressures within subseafloor formations are believed to be an important factor in triggering many of the world's largest and most damaging earthquakes. Fluid flow beneath the seafloor also may help create the conditions that allow vast microbial communities to thrive in subseafloor formations. And it affects the migration of oil and gas and the formation of another common, potentially energy-producing hydrocarbon: gas hydrates. These are ice-like deposits of crystallized methane and water that form under higher pressures and frigid deep-sea temperatures.

Though we know that fluid flow beneath the ocean basins is fundamental and important, our ability to study conditions and processes that occur beneath the seafloor has been limited. To gain a window onto this relatively inac-

cessible domain, we took advantage of holes drilled deep into the ocean bottom by the international Ocean Drilling Program (ODP). The drilling thus did double duty—extracting scientifically valuable seafloor specimens, while simultaneously giving us an entryway for hydrologic experiments within subseafloor formations.

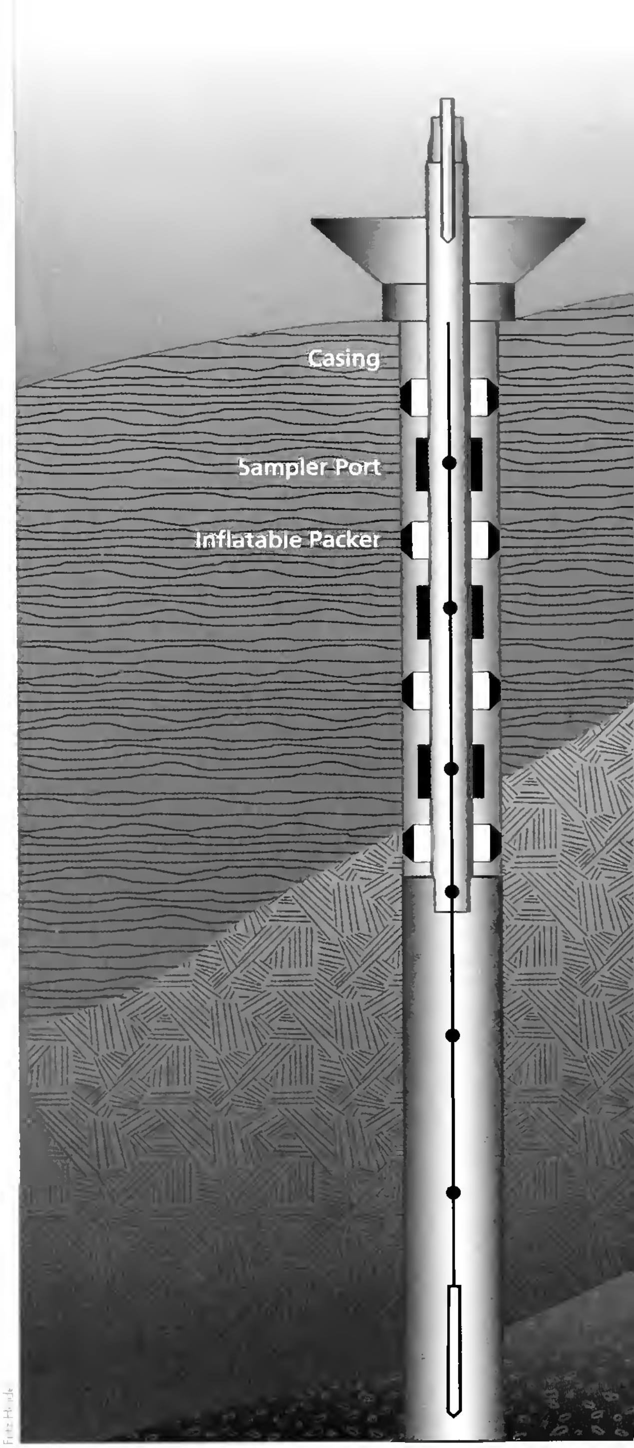
In a previous issue of *Oceanus* (Vol. 36, No. 4) we reported on our early efforts to seal two ODP holes and install instruments in them to create long-term observatories to investigate subseafloor fluid circulation. We called these observatories "CORKs" for Circulation Obviation Retrofit Kits, playing on the obvious analogy of a cork sealing a bottle. For our studies, we had to reseal boreholes because ODP holes left open act as shunts between the oceans and subseafloor formations and disrupt natural hydrological processes. Within the resealed holes, we suspended strings of sensors that were linked to a long-term data logger on the seafloor that could be accessed with a human-occupied or remotely operated vehicle. To date, our sensor strings have been relatively simple. They have included one pressure gauge at the seafloor and one in the sealed hole, temperature sensors distributed down within the holes, and, in some instances, fluid sampling devices near the bottoms of the holes.

Our initial installations were quite successful, and we and our growing group of CORK collaborators have gone on to deploy similar instrumentation in a total of 11 sites (see map opposite) in three representative types of seafloor hydrological environments: spreading centers, where new seafloor is spreading outward from mid-ocean ridges (ODP Holes 857D and 858G), young mid-ocean ridge flanks (395A, 1024C, 1025C, 1026B, 1027C), and accretionary prisms, where sediments scraped off descending seafloor plates accumulate in front of overriding plates, like debris in front of a locomotive's cowcatcher (889C, 892B, 948D and 949C). The CORK program has been an important contribution toward fulfilling the initiative, highlighted in ODP's current Long-Range Plan, for long-term in situ monitoring of geological processes. We gratefully acknowledge solid, forward-looking support from our funding agencies: the National Science Foundation, the Geological Survey of Canada, and the French Institute of Research and Exploration of the Sea (IFREMER), as well as ODP's planning body, the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES).

We emphasize the words "forward-looking," because the CORKs, like other observatories discussed in this issue, require investments not only in equipment and infrastructure, but also in time. They require waiting, possibly for years, before significant results become available. But eight years have now passed since our initial installations, and we have accumulated a growing body of important findings. They are collected in a recent workshop report available on the Internet site of the JOIDES Long-Term Observatories Program Planning Group (vertigo.rsmas.miami.edu/ltoppg.html). Among our more important findings, we have shown that:

- High fluid pressures can build up in the decollement, or plate boundary fault, at subduction zones (Hole 949C in the Barbados prism). This fluid pressure surely is a factor in the genesis of earthquakes that are so common in subduction zones.
- Fluids—driven by small pressure gradients—circulate laterally over many kilometers through the very highly permeable sediments of young oceanic crust in upper "basement" formations beneath the seafloor. This finding gives us a first glimpse of the mechanics of the subseafloor plumbing system, which, among other things, may prove important to vast subseafloor microbial ecosystems.
- Tides in the ocean exert periodic loads on the seafloor that propagate down into sediment and rock layers beneath the seafloor to varying degrees depending on the hydrological and elastic properties of the formations. This unexpected tidally driven flow in the subsurface may play an important role in regulating important subseafloor chemical interactions between fluids and rocks and in maintaining an environment to host microbiological communities. It could also mean that subseafloor formations serve to dissipate a modest amount of tidal energy.

CORKs may represent the best option for in situ sampling of fluids below the seafloor, which has



A new generation of Advanced CORKs will be deployed, starting in 2001. These will have inflatable packers that isolate separate zones in subseafloor formations so that different processes occurring within each zone may be identified.

Aboard the ODP drill ship JOIDES Resolution, *roughnecks position a CORK observatory in a long segmented drill pipe leading to a borehole in the seafloor.*

Ken Becker

proven very elusive to date. Five of the CORKs presently deployed include long-term self-contained fluid samplers suspended within the sealed holes to sample formation fluids (as opposed to the seawater used in the drilling process). Four were just recovered this past September using WHOI's submersible *Alvin* and the wireline Control Vehicle of Scripps Institution of Oceanography's Marine Physical Laboratory (MPL). With access to the sealed holes via a valve at the seafloor, our installations are also excellent for setting up long-term experiments to produce and sample subseafloor formation fluids. Our experience now allows us to predict in which settings sealed holes are likely to produce fluids naturally. In other cases we can take advantage of what we have learned about tidal effects on subseafloor fluid flow to produce subseafloor fluids at the valves.

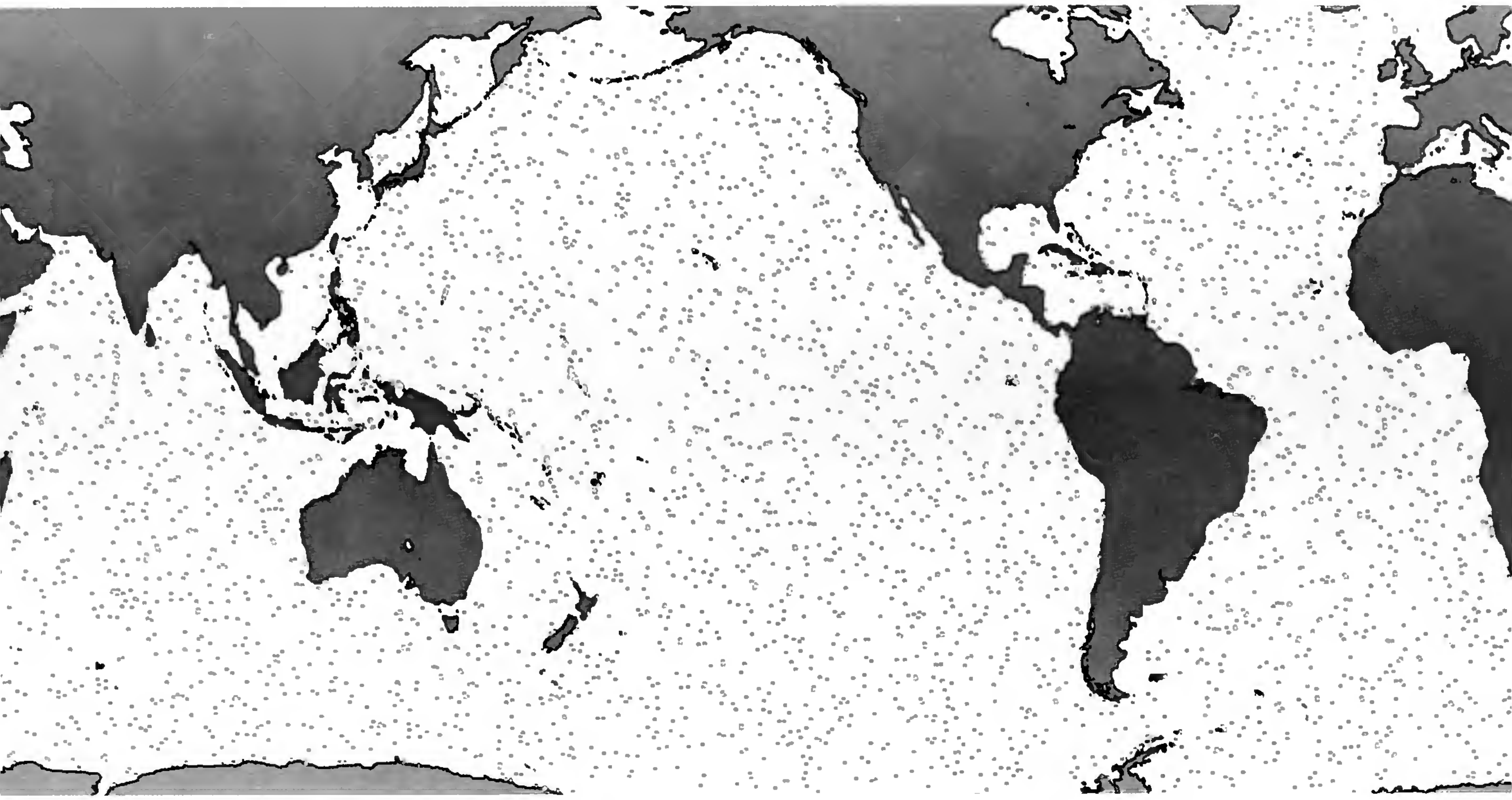
We are gratified at the success of the CORK effort, and are particularly excited to be involving a widening circle of collaborators, ranging from physical oceanographers interested in our deep ocean tidal records to microbiologists interested in microbial systems hosted within the subseafloor formations that we access with the CORKs. However, we recognize that the 1991–1997 CORK design has a key scientific limitation: Until now, our design incorporated a single seal near the top of the hole, and thus our sensors integrate signals from the full range of formations that the hole penetrates beneath the seafloor. But in reality, subseafloor formations are not uniform. Our results and many other lines of evidence clearly indicate that permeability and fluid flow in various subseafloor formations varies because of intrinsic permeability differences in formations or because flow is channeled in discrete faults and fractures.

So we have proposed a new generation of "Advanced CORK" observatories starting with deployments planned for 2001. The next major advances in our understanding of subseafloor hydrology will come not only from expanding the range of in situ measurements and sampling devices incorporated in our sensor strings, but also and more importantly, from incorporating a capability to isolate many separate zones within the subseafloor formations and take measurements in each of them (see diagram, page 15).

Our funding agencies and JOIDES support this strategy, and we are simultaneously developing two technological approaches to implement this multi-sealing capability: a multi-packer instrumented casing system deployed by the ODP drill ship, and a wireline instrumented multi-packer system deployed by the MPL Control Vehicle. The first deployments of the former are scheduled for spring 2001 on ODP Leg 196 in two holes in the Nankai Trough subduction system off Shikoku Island, Japan (site of the Kobe earthquake). First deployments of the latter are scheduled for winter 2001 in a pair of existing young crustal holes in the Panama Basin (504B and 896A).

CORK assemblies await deployment aboard JOIDES Resolution.

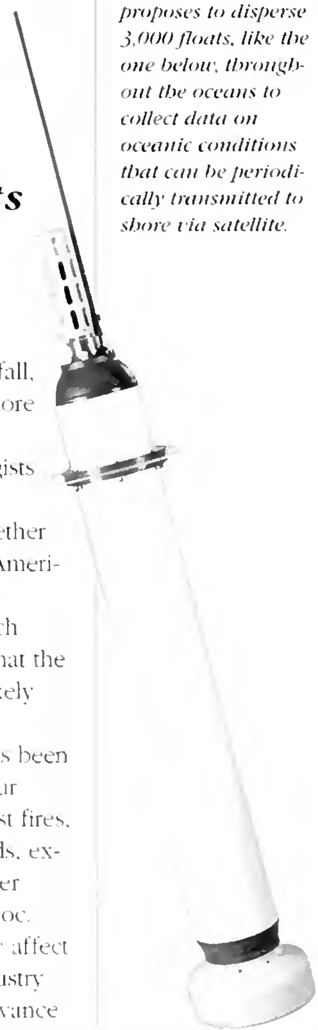
Ken Becker



Launching the Argo Armada

Taking the ocean's pulse with 3,000 free-ranging floats

Stan Wilson, Deputy Chief Scientist, National Oceanic and Atmospheric Administration



The Argo program proposes to disperse 3,000 floats, like the one below, throughout the oceans to collect data on oceanic conditions that can be periodically transmitted to shore via satellite.

Will winter this year be colder and snowier than usual? Should farmers anticipate droughts or floods next spring? Will the fall hurricane season likely be more or less fierce? Should officials conserve water, stock up on fuel, or import grain now to prepare for potential climate conditions a few months hence?

We are on the brink of being able to answer those questions with a high degree of accuracy. But to do that, we can't just look to the atmosphere. We need to look to the ocean.

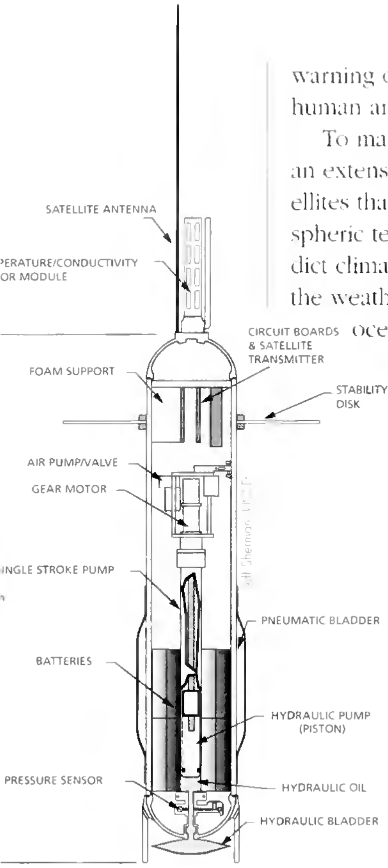
Over the past decade, our evolving understanding of the El Niño Southern Oscillation (ENSO) has revealed how the ocean and atmosphere are intimately linked in a dynamic exchange of heat, moisture, and momentum that generates our climate. But while fast, ephemeral phenomena in the atmosphere produce storms, cold snaps, tornadoes, and other day-to-day events that comprise the weather, the oceans move at a much more lumbering pace. By storing and transferring vast amounts of heat around the planet, the oceans create the underlying conditions that—over seasons, years, or even decades—make broad global patterns of rainfall, winds, storms, and atmospheric circulation more or less likely to occur.

With ever-increasing accuracy, meteorologists have been able to produce three- to five-day weather forecasts. That helps one decide whether to carry an umbrella on Tuesday. But South American farmers—wavering between planting rice (which requires lots of water) or cotton (which doesn't)—would profit greatly if they knew that the coming growing season on average would likely bring more or less rainfall.

The best efforts of humankind have always been humbled by the unexpected vicissitudes of our planet's climate. Droughts cause famine, forest fires, epidemics, mass migrations, even wars. Floods, extended heat waves and cold periods, and other short-term climate shifts wreak their own havoc. Oceanic shifts by themselves can dramatically affect fish populations, disrupting an important industry and food source. In all these cases, a little advance

warning offers a potential means to reduce or avoid human and economic devastation.

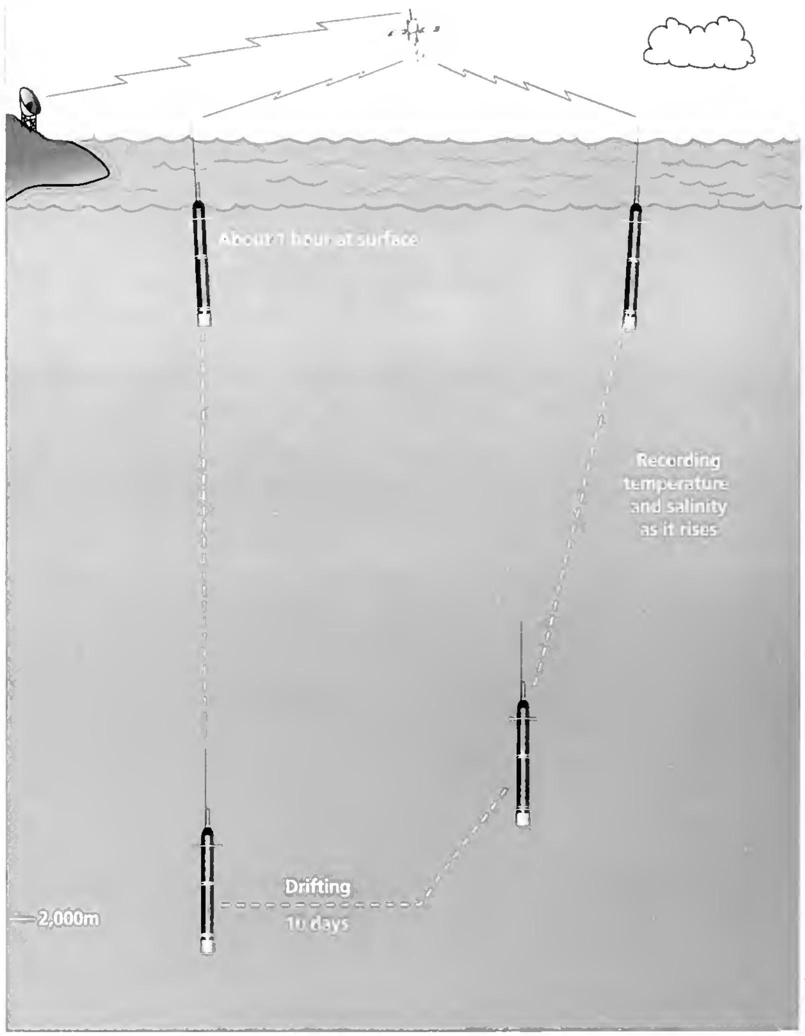
To make their forecasts, meteorologists rely on an extensive network of land-based stations and satellites that collect daily measurements of atmospheric temperatures, humidity, and winds. To predict climate as accurately as we now can forecast the weather, we require a network to monitor global ocean conditions as thoroughly as we monitor worldwide atmospheric conditions.



Above, the principal components of an Argo float. Each float sinks to depths of 2,000 meters, drifts with ocean currents for ten days, rises to the surface taking measurements along the way, and then transmits data back to shore via satellite.

That's the motivation for the Argo program—a Johnny Appleseed-like proposal conceived by an international team of scientists to disperse 3,000 floating buoys throughout the world's oceans. Equipped with sensors to monitor fluctuating temperature and salinity in the upper layers of the ocean, Argo buoys will relay data via orbiting satellites in near real time to shore-based laboratories. Together with satellite and other available data, the Argo observations will be used to make "weather maps" of the ocean, to feed computer climate forecast models, and to improve our understanding of the ocean itself.

Argo is the result of more than two decades of research and development in float technology sponsored by the National Science Foundation (NSF) and the Office of Naval Research (ONR). In the United States, scientists and engineers at Woods Hole Oceanographic Institution, Scripps Institution of Oceanography, and Webb Research Corporation in Falmouth, Massachusetts, have led efforts to design, build, and test the floats. They are designed to sink to depths of 2,000 meters (slightly more than a mile), drift with ocean currents at that depth for ten days, and then rise to the surface, measuring the temperature and salinity of ocean layers along the way. On the surface, the floats radio their data and positions to satellites before returning to depth and continuing another cycle (see diagram, right).



The satellites will relay Argo data to land-based receiving stations and then to scientists and forecast centers in near real time. The data will be openly available, without proprietary restrictions.

Computer model simulations have shown that the floats will not clump, but rather will go with the ocean's flow, maintaining a separation of a few hundred kilometers from each other (see diagram on page 17). Argo floats can be dropped overboard by hundreds of commercial vessels that ply trading routes across the globe, or parachuted by airplanes to seed remote ocean regions (see photos, opposite). They can continue to operate unattended over a design life of four to five years.

Argo was the ship of the mythological Greek hero Jason, and the program's name stresses the close connection between the floats and the Jason-1 satellite, a collaboration between the National Aeronautics and Space Administration (NASA) and the Centre National d'Études Spatiales (CNES, the French Space Agency). Jason-1 will be launched late this year to continue measurements of global sea level initiated by the NASA/CNES TOPEX/Poseidon satellite in 1992. Other satellites operated by NASA, the Japanese Space Agency, and the National Oceanic and Atmospheric Administration (NOAA) measure sea surface temperatures and the speed and di-

rection of winds blowing over the oceans. These satellites will complement the Argo floats, which, unlike the satellites, can observe beneath the surface.

Subsurface measurements are essential because the ocean's upper layers can store 1,000 times more heat than the atmosphere does. Changes in subsurface currents, temperature, and salinity eventually change conditions at the surface, where the ocean interfaces with the atmosphere.

When an El Niño occurs, for example, a great mass of warm water, usually pooled in the western Pacific, spreads eastward, accumulating off the west coast of the Americas. At the same time, prevailing trade winds diminish, rearranging global atmospheric circulation patterns and worldwide weather. Rain clouds, for example, accompany the warm waters eastward, taking rain from places where it is expected and dropping it unexpectedly in others.

George Tupper

As recently as 1982, scientists were unaware that one of the most powerful El Niños of the century was forming with inevitable and catastrophic momentum. It sparked climatic changes that caused devastating droughts and fires in Australia, flooding in normally arid regions of Peru and Ecuador, unusual storms that rearranged California beaches, and widespread mortality of fish and bird life. All told, it led to thousands of deaths and an estimated $13 billion in damage.

In the aftermath of this disastrous El Niño, NOAA, NSF, and international partners began to deploy an extensive observing system—moored instruments, surface drifting buoys, and Volunteer Observing Ships—to monitor oceanic conditions spanning 10,000 miles of the equatorial Pacific. These complement NASA, NOAA, French, and Japanese satellites that track shifting winds and sea levels. Completed in 1994, this ENSO Observing System provides a continuous stream of real-time observations to forecast the development, strength, and duration of El Niños and La Niñas, a cooling of eastern Pacific waters that sometimes follows an El Niño episode and causes its own set of weather conditions.

The monitoring system provided advance warning of the powerful 1997–98 El Niño, which helped save an estimated $1 billion in California alone.

Building on this success in unraveling ENSO, meteorologists and oceanographers have begun to identify a host of other ocean-atmosphere oscillations operating in the earth's climate system: the North Atlantic Oscillation, the Arctic Oscillation, the Antarctic Oscillation, the Pacific Decadal Oscillation, the Indian Ocean Dipole, and the Antarctic Circumpolar Wave. Shifting over months or decades, each is associated with different climate changes in different parts of the globe in quasi-periodic, but *potentially predictable* ways.

Webb Research

The Argo program offers a means to gather the consistent, long-term, observations within the upper layers of the global ocean needed to reveal the ocean's role in these newly identified climate oscillations and to incorporate their effects into climate forecasts. Once fully deployed, Argo and its satellite partners will give us for the oceans what meteorologists have had for the atmosphere—a worldwide observing network and the potential to forecast our climate six to 12 months in advance.

More information on the Argo program is available at: www.argo.ucsd.edu.

Argo floats (like the prototype above in the Labrador Sea) can be deployed by ships, or parachuted by airplanes (below) to seed more remote ocean regions.

A WHOI moored surface buoy equipped with meteorological and underwater sensors is deployed in the eastern tropical Pacific Ocean from Scripps Institution of Oceanography's R/V Roger Revelle. *Fixed in strategic ocean locations, surface and subsurface moored observatories (see diagram opposite) can track oceanic processes and air-sea interactions that influence Earth's climate.*

Outposts in the Ocean

A global network of moored buoy observatories to track oceanic processes that affect our climate

Robert Weller, John Toole, Michael McCartney, and Nelson Hogg
Senior Scientists, Physical Oceanography Department, WHOI

Oceanographers and climatologists have something in common with politicians and stock market analysts: They are all trying to get a grasp on a complex, ever-shifting system.

To gauge the ebb and flow of public opinion, politicians today are constantly polling constituents. To track fluctuating financial markets, analysts receive a continual flurry of global economic data and information on companies and markets.

For oceanographers and climatologists, one of the most urgent goals is unraveling the ocean's crucial role in shaping our climate. To predict climate changes or extreme weather events that may have potential societal impacts, scientists desperately need the same sort of detailed, ongoing information that politicians and economists have to investigate their systems.

Specifically, oceanographers require long-term measurements to understand processes and changes that occur in the oceans over seasons, years, decades, or longer. Among the important climate questions oceanographers seek to answer are these: How does the ocean store and transport vast amounts of heat and fresh water around the globe? How do the ocean and atmosphere exchange heat, fresh water, and momentum? How are changes in ocean temperatures and salinity, ocean circulation, and climate all interrelated? Are long-term changes in the oceans naturally occurring, or are they the result of human activities, such as the buildup of greenhouse gases in the atmosphere?

Today, the world's oceans are sparsely observed. Oceanographers lack the means to gather the fundamental measurements they need to examine their system—putting scientists in the position of working on mysteries without many essential clues.

But a major effort is under way to establish a Global Ocean Observing System (GOOS)—a worldwide network that would collect the vast, far-flung, ever-changing data necessary to understand the

processes by which the oceans help create climate conditions. GOOS would combine a variety of instrumentation. It would include satellite systems providing global coverage of the ocean surface, flotillas of oceanographic instruments drifting throughout the oceans, and autonomous ocean observatories moored at strategic sites in the ocean.

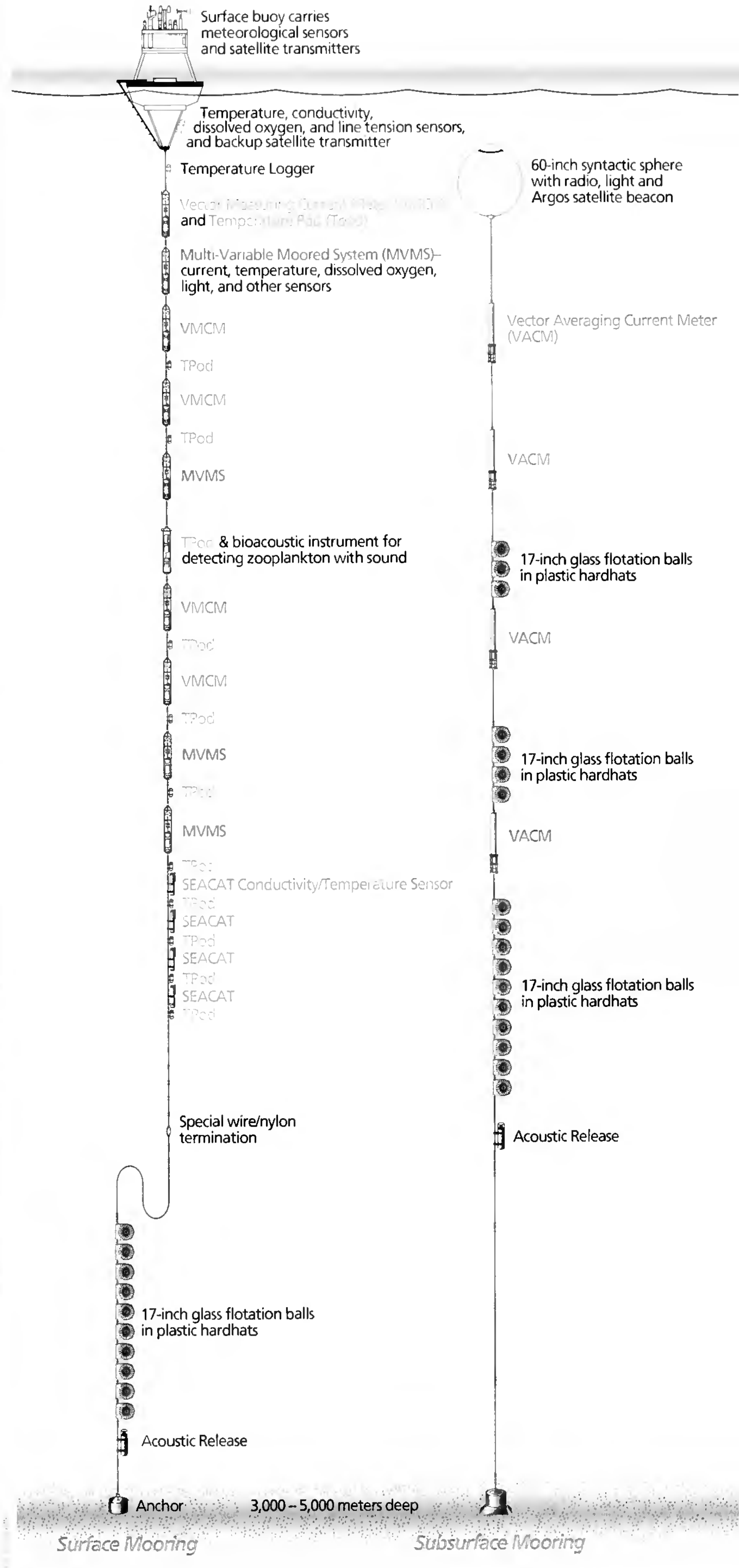
Fixed observatories moored at key geographic sites around the globe are unique in this mix of instrumentation because they can provide highly detailed observations of atmospheric processes just above the sea surface, as well as oceanographic measurements from the seafloor to the sea surface. Measurements collected at fixed sites over long time periods are particularly important for oceanographers trying to understand air-sea interactions, as well as relatively slow-evolving oceanic processes.

In the past, a network of ocean weather stations (OWSs) provided a treasure trove of data for oceanographers and played an essential role in early efforts to build initial understanding of how the ocean changed over time and how it responded to, and in turn influenced, atmospheric changes (see *Oceanus*, Vol. 39, No. 2). Primarily to guide trans-ocean-voyaging aircraft after World War II, the US and four other countries established 13 sites in the North Atlantic and the Pacific Oceans (labeled alphabetically, starting with "A") that were constantly occupied by ships. Planes would check in with ships to receive a position and weather data. Ship crews used weather balloons to gather air temperature, humidity, pressure, and wind direction and speed, and, while on site, they also collected a wealth of oceanographic measurements.

Unfortunately, by the 1970s satellites began to provide jet aircraft with the positioning and weather information they needed. The original reasons for maintaining the OWSs disappeared, and the program ended in 1981. The last remaining active station, OWS M off Norway, will end ship-based observations in 2000, and with it, the last vestige of a valuable system to collect long-term oceanographic data will disappear.

To fill the void in the future, we envision that among critical GOOS components will be a combination of free-drifting, or "Lagrangian," platforms (such as the Argo floats described on pages 17–19), and fixed, or "Eulerian," platforms, such as surface and subsurface moorings. (The names derive from two 18th century mathematicians, Euler and Lagrange, who originated alternative ways of measuring fluid flow—past a fixed point and between two points.)

Eulerian observatories are not new to ocean sciences. They have been, and remain, one of the major elements in developing theoretical understanding of the oceans. In the tropics—motivated by the need to improve our ability to predict El Niño events—we have already constructed a new net-



work of Eulerian observatories to obtain surface wind and upper ocean temperature observations. In the 1980s, the National Oceanic and Atmospheric Administration, the National Science Foundation, and international partners began to install the Tropical Atmosphere Ocean (TAO) array of more than 70 surface moorings in the equatorial Pacific. Completed in 1994, it provided the observations that helped give us advance warning of the powerful El Niño of 1997–98. The goal now is to build on TAO and occupy more sites across the world's ocean to create a network of Global Eulerian Observatories (GEO) (see map below).

A proposed network of fixed moored ocean observatories would be chosen among potential sites (red dots), whose strategic value for monitoring and understanding the ocean's role in climate has already been identified. The new sites would complement the existing Tropical Atmosphere Ocean (TAO) array of buoys in the tropical Pacific Ocean (shaded region) and the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) (shaded region), whose deployment began in 1997.

Such observatories come in two types (see page 21). Since the 1960s, scientists have used subsurface moorings to observe ocean currents and water properties. These are instrumented cables, anchored to the seafloor and attached to buoyant floats, that reach upward toward, but not to, the sea surface. In contrast, surface moorings have surface floats with downward-hanging cables. Instruments along the submerged cables measure water temperature and salinity, and the speed and direction of currents. The surface floats additionally provide a platform for sensors that measure wind speed and direction, incoming shortwave radiation, incoming longwave radiation, relative humidity, air temperature, barometric pressure, and precipitation. The technology to make such meteorological observations, which was not even available until the 1970s, has improved significantly over the past 15 years, giving scientists the capacity to make highly reliable and accurate measurements.

Both types of mooring technologies have matured to the point where they can measure atmospheric and/or oceanic changes as frequently as once per minute and can take oceanographic measurements meter-by-meter in the water column. Both are now capable of sustained operation for long time periods.

Sensors on surface buoys now perform reliably for periods of six to 12 months. Data are both transmitted via satellite and recorded on board. A recent deployment of surface buoys in the Arabian Sea showed that they can perform well in severe environments. And it also demonstrated their ability to collect detailed measurements of previously undetected air-sea processes. Incorporating these previously overlooked processes into numerical weather prediction models will produce significantly more accurate forecasts.

Unlike surface moorings, which are exposed to winds, salt spray, surface wave motion, fouling by marine growth, and disturbances by vandals, subsurface moorings are subject to less stressful conditions and now routinely collect information for periods of up to two years without servicing. In the past 30 years WHOI alone has deployed almost 1,000 subsurface moorings in all parts of the world's oceans. Information gathered from them has been used to begin to understand how the oceans change over space and time—with an emphasis on time scales of less than a year or so. In some parts of the ocean, such as the northwest North Atlantic, we have made enough measurements to be able to construct a three-dimensional "picture" of the ocean's mean circulation and to estimate the speed and volume of waters transported by important currents.

For subsurface moorings, a new class of observing system is approaching operational status: moored profiling instruments. These devices, fitted with a suite of oceanographic sensors, move vertically along conventional mooring cables, returning measurements of water properties and ocean currents at very closely spaced intervals throughout the water column (see photo and diagram opposite). Using one mobile set of sensors versus many stationary, separate sensors not only reduces costs, it also removes the need to calibrate many different sensors to make sure their measurements are of comparable quality.

In each deployment, these instruments can make approximately 200 top-to-bottom ocean profiles—akin to those obtained from ships. Second-generation instruments may double this capacity. The addition of a bottom pressure sensor would grant the capacity to monitor fluctuations that are not dependent on depth (such as a tidal current, which has the same magnitude and direction throughout the water column), as well as fluctuations that do vary with depth (such as internal waves, moving beneath the surface and within the ocean, whose speed and direction may vary at different depths). The instruments can make such fine-scale observations of current velocities that scientists will be able to detect internal wave motions, as well as other

flows that occur only infrequently. They will also be able to detect subtle variations in eddies—smaller-scale, episodically occurring currents that move contrary to main currents.

With these tools available, the international focus is now on identifying the strategically best GEO sites to investigate one or more of the four important scientific objectives listed below.

Direct measurements of ocean currents

At strategic sites, moored buoys can directly measure ocean currents flowing at the surface or down into the ocean's interior. These currents redistribute heat and fresh water around the globe. In particular, the ocean and atmosphere help maintain the planet's thermostatic balance by absorbing heat in the sun-drenched tropics and moving it toward Earth's poles. Cooler (and denser) waters sink and flow back equatorward.

The details of these processes are not yet fully understood, yet they are the underpinnings of our climate system. We need, for example, long-term Eulerian observatories to measure the dense overflows of cold Norwegian Sea waters as they move south through the Denmark Straits and Faroe Bank Channel. We also need moored stations to measure variations in the poleward transport of warm water in currents, such as the Gulf Stream, that hug the western boundaries of continents.

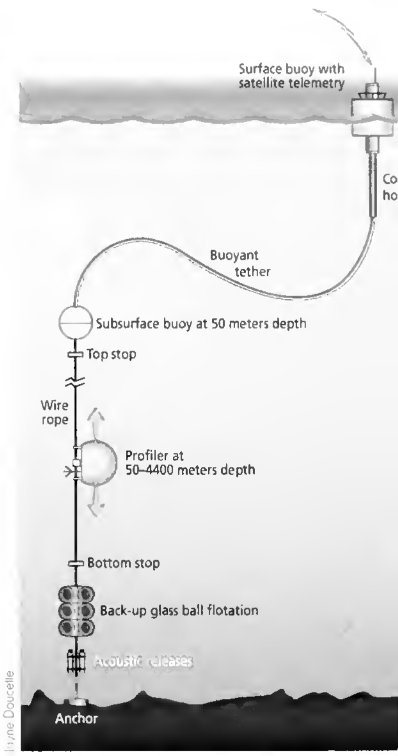
Examining 'water mass formation'

In some locations in the world ocean, surface waters become colder or saltier (and therefore denser) than surrounding waters and actually sink and flow into the ocean's interior—a process known as water mass formation or transformation. This happens when the atmosphere cools the waters or where evaporation or sea ice formation leaves salt behind. Winds can also push surface waters together, and these convergent flows force surface waters downward.

Like a hand pushing down in a bathtub, the downward flow of waters from the surface to the interior of the ocean provides the propulsion to redistribute heat and fresh water throughout the ocean and around the world. In this way, the oceans can absorb heat from the atmosphere in the tropics, for example, and release it back to the atmosphere over the North Atlantic decades to hundreds of years later. Moored ocean observatories in key sites of water mass formation and/or transformation could observe the slow variations in the process—documenting the depth to which cold water sinks and chronicling changes in ocean heat and fresh water content over time.

Obtaining measurements of air-sea interactions

Meteorological data obtained above the sea surface would provide accurate measurements of the heat and fresh water exchanged between the ocean and atmosphere. Deployed in regions where surface waters sink, these would help quantify the rate at which water mass transformation occurs. In other sites, these measurements would provide high-quality, accurate reference data to check, verify, and calibrate meteorological measurements taken by Volunteer Observing Ships (VOSs) and by satellites. They would also gather the actual data that provide reality checks for computer models that forecast weather and climate.



Jayne Doucette

Moored profilers move vertically along mooring cables and measure water properties and currents throughout the water column.

Investigating variability of the ocean's interior

Oceanographers believe that heat can be moved north and south not only by currents, but also by smaller, more-difficult-to-discern eddies within the oceans. With their ability to make frequent, detailed measurements of water velocities and properties throughout the water column, moorings can detect and document the presence and dynamics of eddies around the world. This will give us our first glimpse into understanding how eddies influence ocean transports of heat and fresh water. It will also provide initial data that can serve as benchmarks for developing numerical models of ocean dynamics—which in the future will be run on computers sufficiently powerful to include finer-scale dynamics such as eddy variations.

Today deep-sea currents have been observed over periods of more than two years at only a few locations. The longest available record is about 10 years. But new cost-effective subsurface moorings being developed by Nelson Hogg at WHOI are expected to permit moorings to last more than five years, with the capability for frequent data transmission back to the lab. GEO sites equipped with these new subsurface moorings could start to obtain the first global picture of long-term internal variability of the oceans.

We acknowledge NOAA, NSF, and the Office of Naval Research for continuing support for the development of the technologies needed to make global ocean observations and for the research to improve understanding of the ocean and its impacts.

Tom Kleindinst

Research Engineer Steve Liberatore, left, and Research Associate Terry Hammar test a moored profiler in Woods Hole.

Where the Surf

Britt Raubenheimer, Assistant Scientist, and Steve Elgar, Senior Scientist
Applied Ocean Physics and Engineering Department, WHOI

William Birkemeier

The gentle lapping of waves on the beach is a metaphor for enduring tranquility. However, the thin zone where the surf meets the turf is one of the most turbulent, complex, fast-moving, constantly changing places on Earth.

The nearshore region (between the dry land above the beach and the relatively deep water in the coastal ocean) is continually subjected to large waves, strong winds, and vigorous currents that stir up and transport massive amounts of sand—creating and destroying dunes on the beach and sandbars in the surf, or changing their shapes and positions. Shifting sandbars, in turn, change the topography of the seafloor, altering the direction of currents and causing waves to break in different locations with varying intensities. Thus, changes in one variable affect many others in [illegible]ose systems. In the process, sand is [illegible] from some beaches and given to others, [illegible]me beach is alternately eroded or built [illegible] times.

Unraveling the physics of these nearshore processes offers valuable societal benefits. More than half the world's population lives within 100 miles of the coast. More than $2 billion is spent annually to restore eroded beaches and to build jetties, breakwaters, and other structures that may prevent erosion and protect property. Beaches also have military importance, serving as strategic landing zones.

With dual goals of safeguarding civilian property and supporting military operations, the Army Corps of Engineers has established facilities to conduct research and testing. Among these is the Field Research Facility (FRF), a former Navy bombing range on a 176-acre beach site in Duck, North Carolina, which the Army Corps converted into a unique natural laboratory to study nearshore processes. Its primary mission is to collect measurements of waves, currents, winds, tides, sand levels, and other phenomena in an effort to improve understanding of the processes that affect beaches.

Although scientists can learn a great deal from laboratory experiments, theoretical studies, and computer simulations, they need field

Meets the Turf

William Birkemeier

Above, an 1,840-foot pier bisects 3,000 feet of beachfront at the Army Corps of Engineers' Field Research Facility in Duck, N.C., where scientists explore coastal processes that affect beaches. A cranelike device on the pier (far left) deploys instruments into the ocean. At left, scientists and divers set up a series of metal-pipe scaffolds at intervals from the beach out into the ocean. Instruments mounted on the scaffolds collect data on currents, waves, seafloor topography, and other phenomena to unravel the complex forces that shape coastal areas.

Aerial photo: RC-30 large-format camera photo provided by Pacific [illegible]

Among the specialized equipment at the Army Corps of Engineers' Field Research Facility is a motorized, three-wheeled vehicle with a stable platform atop a 35-foot tripod frame. The Coastal Research Amphibious Buggy, or CRAB, can be driven from the beach into the ocean, in wave heights up to six feet, to install and service instruments, to collect sediment samples, or to map the ocean bottom.

measurements to test the results of these studies and to determine the relative importance of various processes on natural beaches. However, large waves and evolving conditions make it difficult to install and maintain instruments, particularly during Nor'easter storms and hurricanes when the most dramatic beach changes occur.

For the past 20 years most of the large US nearshore field experiments have been conducted at the FRF. Scientists from around the world, including several from WHOI, have come to Duck to do research, attracted by the FRF's specialized equipment, experienced staff, and unique capabilities. The 3,000 feet of waterfront is bisected by a 1,840-foot pier extending from the dunes on the beach to water depths of about 23 feet (see pages 24–25). A cranelike device mounted on railroad tracks along the pier, called a Sensor Insertion System (SIS), can deploy instruments in precise locations in the ocean up to 75 feet on either side of the pier (see photo, page 24).

The FRF also offers specialized vehicles, including the Lighter Amphibious Resupply Cargo (LARC) ship, which can be loaded on shore and driven through the surf into deeper water, and the Coastal Research Amphibious Buggy (CRAB), a motorized, three-wheeled vehicle with a stable platform atop a 35-foot tripod frame (photo at left). The CRAB can be driven from the beach into the ocean, in wave heights up to six feet, to install and service instruments, to collect sediment samples, and to map the ocean bottom.

Observations are collected continuously with permanent instruments, providing a long-term, ever-growing data set of coastal changes. A waverider buoy located approximately a mile offshore of the FRF and pressure sensors in shallow waters are used to study the evolution of waves traveling from the deep coastal waters across the surf zone to the shoreline where they run up the beach. A tide gauge at the pier end measures fluctuating tidal elevations that are important to nearshore processes. Multiple video cameras mounted on a 140-foot-tall tower on shore record breaking waves and shifting sandbar locations. Changing sand levels from the beach out to 26-foot water depths are surveyed with the CRAB. Air temperature, atmospheric pressure, rainfall, winds, and other meteorological data are measured routinely. These data have been used, for example, by WHOI Associate Scientist Jim Edson and FRF Research Oceanographer Chuck Long to study interactions and exchanges between the air and ocean.

The FRF's continuous, long-term observations have been complemented by short, intense experiments. In 1994, scientists from many institutions convened at Duck to conduct an ambitious experiment to study the surf zone. Author Steve Elgar, now a Senior Scientist at WHOI, and Bob Guza of the Scripps Institution of Oceanography (SIO) used the CRAB and the LARC to deploy several metal-pipe scaffolds, each supported on six 20-foot-long, metal-posts inserted into the seafloor (see photo, page 25). Mounted on the scaffolds, which were located at intervals between the beach and 25-foot water depths, were current meters to measure the speed and direction of currents, sonar devices that use sound to record the changing seafloor topography, and pressure sensors that measure waves and water levels by measuring the weight of water above them.

With this instrument array, Elgar, Guza, and Edith Gallagher of the Naval Postgraduate School documented how offshore-directed currents (undertow) moved sandbars out to sea during storms. In one case, storm-related undertows moved a six-foot high sandbar about 100 yards seaward.

Combining observations from the surf zone array

with measurements from the FRF's permanent sensors. WHOI Associate Scientist Steve Lentz and author Britt Raubenheimer, now an Assistant Scientist at WHOI, showed that breaking waves cause mean water levels to increase by more than a foot in the surf zone. Using instruments deployed farther offshore, Lentz determined the relative effects of breaking waves, winds, and the earth's rotation on ocean circulation on the inner continental shelf. WHOI Senior Scientist and biological oceanographer Cheryl Ann Butman showed that wind-driven currents controlled the onshore and offshore transport of clam, snail, and worm larvae.

Building on what was learned during Duck94, FRF conducted an even larger experiment during fall 1997. More than 250 scientists, technicians, students, divers, and others deployed over 400 sensors. Using the CRAB, the authors and Guza installed more than 200 sensors to measure waves, circulation, water table fluctuations, and changing sand levels. WHOI Associate Scientist John Trowbridge investigated bottom stress associated with breaking waves and wind-driven currents using instruments mounted on a 1,000-pound frame deployed with the CRAB. Additional sensors deployed by other investigators included scanning acoustic altimeters to map the movement of ripples on the seafloor, and fiber-optic backscatter sensors to measure the amount of sand suspended and transported in the water above the seafloor. Frequent sand samples were collected from the CRAB and by divers to determine sediment grain sizes, which affect the amount of sand that can be lifted off the bottom and moved by waves and currents.

The more details we learn about nearshore physics, the more we will be able to elucidate the mechanisms that cause erosion or coastal damage, and begin to predict and prevent them. The fundamental physics learned at Duck is applicable to many beaches around the world that have similar characteristics and wave conditions. The FRF has established a beachhead of knowledge to solve problems that once seemed too complex to grasp.

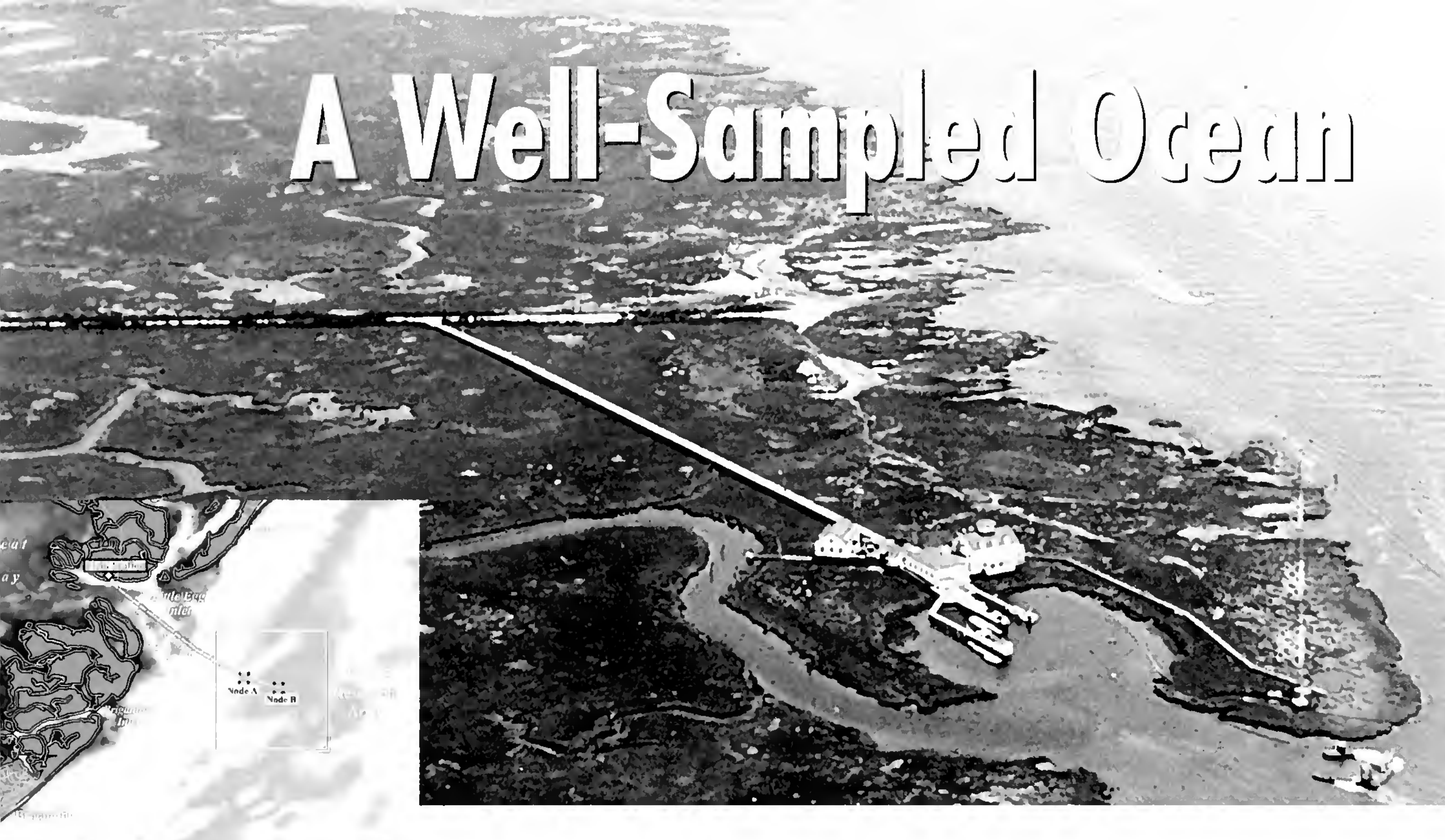
Information on the FRF is available at www.frf.usace.army.mil.

The authors thank William Birkemeier, director of the Field Research Facility, and WHOI Senior Scientist Cheryl Ann Butman, who provided helpful comments. The Office of Naval Research, the National Science Foundation, and the Army Research Office have supported our research.

Waves, currents, sand grain sizes, sandbar configurations, water table levels beneath the beach, and other phenomena combine in complex ways, causing very different patterns along the same beach.

A diver services instruments collecting data in the surf zone.

A Well-Sampled Ocean



Rutgers University's Marine Field Station in Tuckerton, New Jersey, is the headquarters of the Long-term Ecosystem Observatory (LEO)—a network of sensors taking continuous, real-time observations of a swath of coastal ocean. A backbone component of LEO is a subseafloor cable supplying power and two-way communications from the field station to permanent seafloor nodes, which, in turn, support a variety of instruments.

The LEO Approach

Scott M. Glenn, Professor, Institute of Marine and Coastal Sciences, Rutgers University
J. Frederick Grassle Director, Institute of Marine and Coastal Sciences, Rutgers University
Christopher J. von Alt Principal Engineer, Applied Physics and Ocean Engineering Department, WHOI

Unlike the oceans, the sky is relatively visible and accessible to us. We are well acquainted with the range of processes that occur in the earth's ever-changing atmosphere. We know about rainstorms that slow daily commutes and even have a growing awareness of the long-term potential dangers of global climate change. Radio, television, and the World Wide Web provide instant access to weather conditions and forecasts on demand. Airplane pilots, farmers, or people planning outdoor activities can immediately assess the value of these forecasts simply by looking out their windows, and, if necessary, they can adjust their plans based on local conditions. Daily observations and experience, combined with readily available weather forecasts, both short- and long-term, have given us a common-sense knowledge of how the atmosphere works and an ability to make informed judgments on how best to proceed in the face of present conditions.

But in the ocean, the situation is quite different. Conditions and processes at work on any given day in the ocean are usually a mystery to us. Satellites may observe the surface ocean from space, but what is happening below the surface, out of sight of our orbiting viewers? Unlike the atmosphere, much of the ocean is not routinely monitored or sampled, so the only way to learn what might be going on in a particular ocean location is to visit it by boat, and, if weather conditions are especially good, dive under the ocean surface. But diving vehicles are expensive, and they provide only a fleeting glimpse of a largely unknown environment. Short-term events may not occur during a research cruise, and thus remain undetected. Critical trends that occur over large areas and long time periods are difficult to confirm with spotty coverage from ships and ocean moorings.

What we require are permanent windows on the sea to help us develop the same instinctive, common-sense feel for the ocean that we have achieved for the atmosphere. That was a fundamental goal of scientists, engineers, and educators who designed and built Rutgers University's Long-term Ecosystem Observatory (LEO-15).

The concept began during a conversation in 1986 between authors von Alt and Grassle, then a Senior Scientist at WHOI, who envisioned a net-

work of underwater observatories from which robots could be deployed and directed by computers anywhere in the world. These visions became a joint research program funded by the National Science Foundation in 1992. Additional support has come from the National Oceanic and Atmospheric Administration, the Office of Naval Research, the National Ocean Partnership Program, and Rutgers University. Installation and construction of LEO-15 started in 1994.

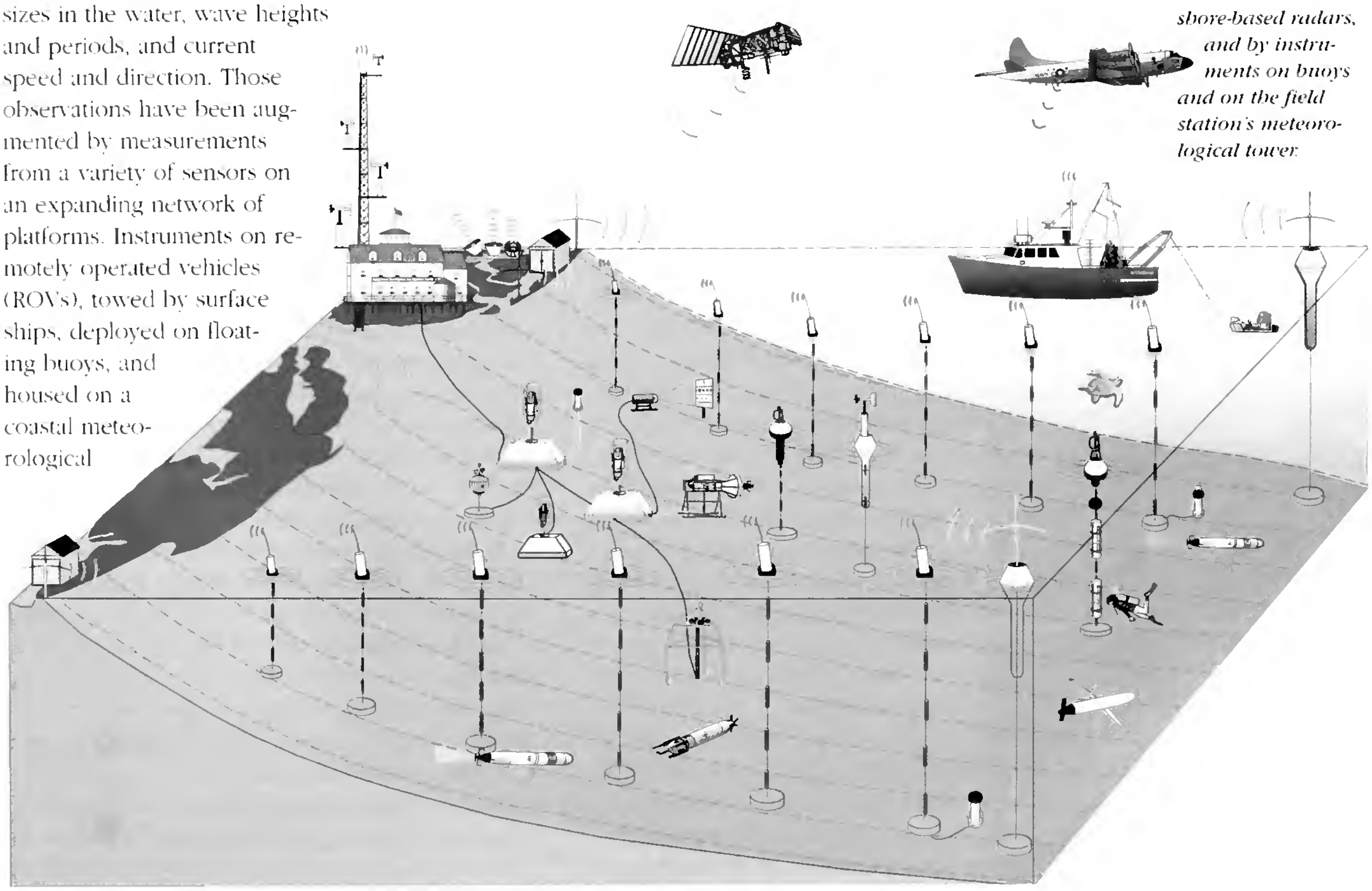
The "15" comes from the system's original and still central components: permanent seafloor nodes at 15 meters depths about 9 kilometers off the coast of Tuckerton, New Jersey. A buried subseafloor electric/fiber-optic cable extending from the field station in Tuckerton provides continuous, ample power to the nodes, which support instruments, other remote platforms, or Autonomous Underwater Vehicles (AUVs). The cable also provides two-way, real-time, high-bandwidth communications (including video) between the nodes and the field station. Linked to the Internet, the system gives scientists the ability to monitor and control experiments and vehicles from any laboratory in the world. Instantaneous distribution via the World Wide Web also offers educators and the public a direct link to the undersea world off New Jersey from classroom or home computers.

Instruments supported by the nodes measure water temperature and salinity, chlorophyll, dissolved organic material, fluorescence, and particle sizes in the water, wave heights and periods, and current speed and direction. Those observations have been augmented by measurements from a variety of sensors on an expanding network of platforms. Instruments on remotely operated vehicles (ROVs), towed by surface ships, deployed on floating buoys, and housed on a coastal meteorological tower all contribute data, as do satellites and shore-based radar remote sensing systems, which can tell us about sea surface temperature, water quality, and phytoplankton content over wide areas.

Together, this network now lets us continuously sample a 30-by-30-kilometer research area spanning water depths of 3 to 30 meters. This region, the inner continental shelf, has often been ignored in the past because its complex dynamics and turbulent waters have made both scientific studies and operating conditions difficult. Yet it is a region that has important impact on people.

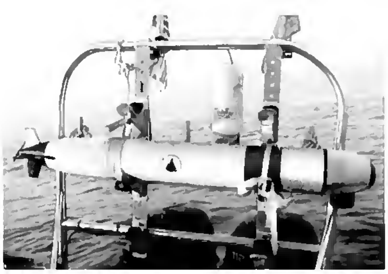
Much the way meteorologists use continuously available atmospheric data to create weather forecasts, we can assimilate ocean data into numerical computer models that simulate ocean dynamics and generate forecasts of ocean conditions that would be useful to fishers, beach visitors, scientists, and others. In a well-sampled ocean, developing trends from model-generated forecasts can be compared with the trends in rapidly updated observations to see where the model is staying on track, and where it is drifting away from observed behavior. Just as weather forecasters develop a feel for the biases of different atmospheric models, ocean forecasters will start to develop the same feel for ocean models.

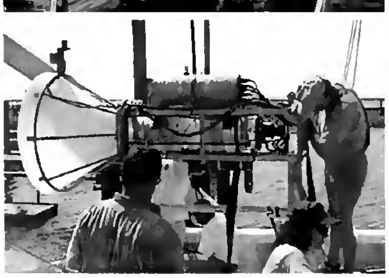
The ability to operate in a well-sampled ocean profoundly affects ocean research. Ocean models use the laws of physics to extrapolate how current conditions will likely evolve into future conditions. But because the ocean is under-sampled, models



At LEO, instruments supported by permanent seafloor nodes are complemented by a wide range of measurements taken by robotic vehicles, satellites, aircraft, research vessels, shore-based radars, and by instruments on buoys and on the field station's meteorological tower.

Above, LEO's cable from the field station is directionally drilled underneath a marsh and intercoastal waterway and toward the continental shelf in 1994. Below (top to bottom), the WHOI-designed remotely operated vehicle REMUS (Remote Environmental Monitoring UnitS); an underwater docking station where REMUS can upload power or download data; one of LEO's seafloor nodes is deployed.





may start with incorrect initial conditions and end up off course.

Because intensive sampling of given ocean regions is too expensive, a science called "adaptive sampling" has evolved. Adaptive sampling uses model forecasts to identify regions where additional data are critical, so that scientists can focus their limited sampling resources in these critical regions and improve the model forecasts at reduced cost.

In the well-sampled ocean, errors in initial ocean conditions would no longer poison the accuracy of ocean model forecasts from the start. Instead, errors would more likely result from imperfect understanding of the physical processes going on in the ocean. That fundamentally shifts the still critical role of adaptive sampling: Instead of focusing on sampling to improve the accuracy of initial conditions, adaptive sampling systems could focus on regions where crucial physical processes are poorly understood or highly sensitive. These measurements would improve scientists' ability to understand underlying physical processes, to verify the models' accuracy, and to keep the models on track if their results begin to deviate from observed conditions.

Once we begin to get our own common-sense feel of ocean processes, we can begin to ask what a fish, diving bird, porpoise, clam, or starfish sees during a lifetime in the ocean. With our air-bound sensory equipment and inability to be present during many important oceanic events, we have not been able to visualize, let alone experience, the habitat of any ocean creature.

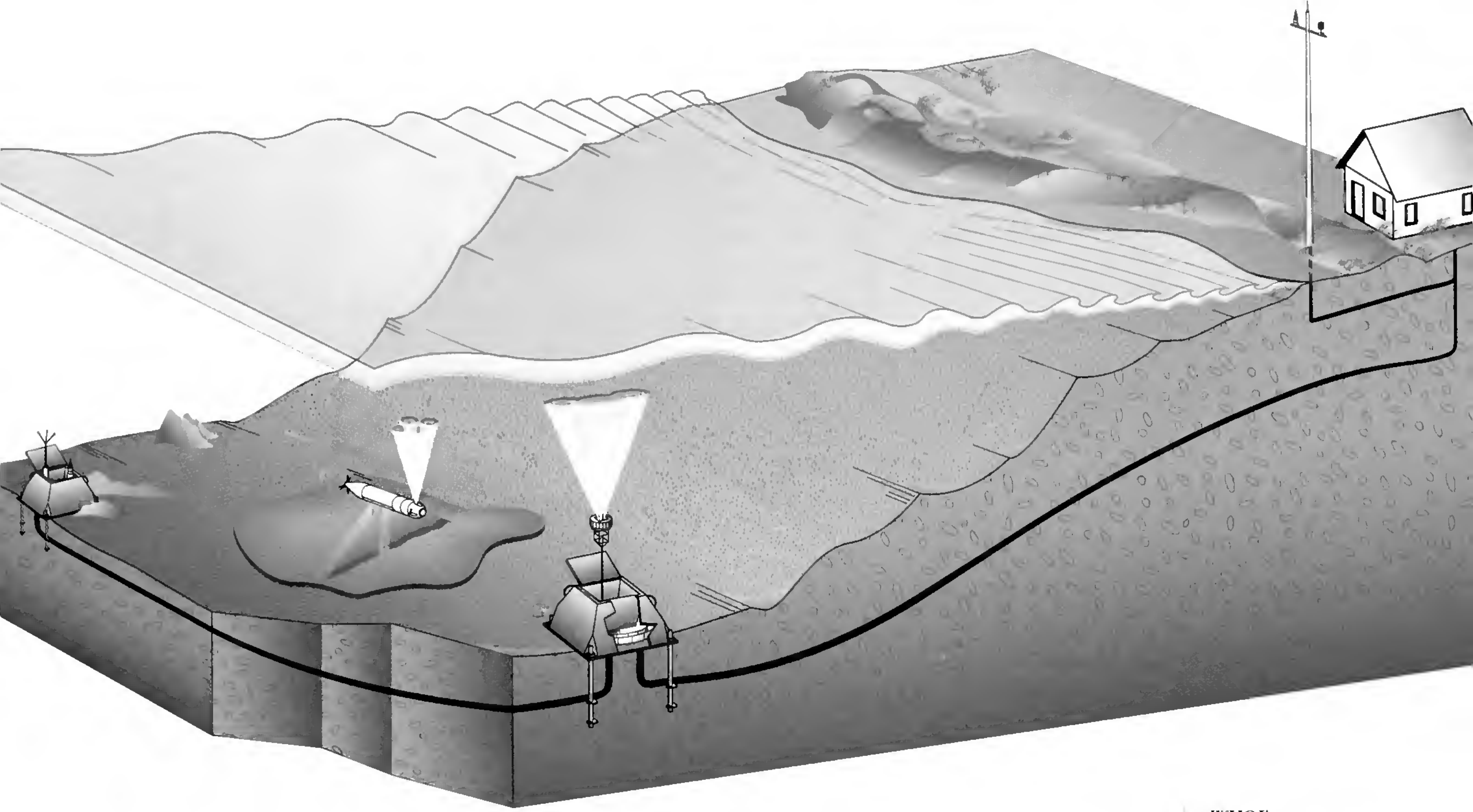
Whenever scientists have had a more continuous presence in the marine environment, major advances in understanding have occurred. Frequent visits to intertidal rocky shores to conduct experiments have demonstrated the importance of interactions among individuals of different species with each other and their environment. Underwater observations by divers on a daily basis have provided insight into the behavior and life cycle of reef fishes and corals. From the submersible *Alvin*, deep-sea ecologists received their first view of the ocean floor and the responses of some of the inhabitants to their surroundings. These advances were achieved simply by extending our visual and manipulative capabilities into the ocean. With LEO technologies, the environments not visible to human eyes can be visualized and studied remotely for the first time.

Our inability to routinely observe the ocean and its life compromises our ability to apply usual land-based management practices in the marine environment. We once believed the oceans could sustain any demand on their resources and could accommodate all but the most extreme assaults from exotic chemicals and any amount of excess nutrients. These ideas turn out to be untrue. The success of our ports requires efficient, safe traffic management, reduced sediment contamination, and better methods for using dredged material beneficially. Coastal economies will benefit from real-time information about beach conditions. Better tools for predicting and rapidly responding to coastal hazards such as storms, erosion, toxic algal blooms, and oil spills can minimize the harm they cause. Naval commanders have enormous interest in new methods to reconnoiter unfamiliar and possibly mined beach landing zones. Improved understanding of marine ecosystems and the need to manage living marine resources requires information about the habitats of all stages in the life cycle of each species and about the interactions among species and their physical surroundings.

With additional new technology (high-resolution color satellites, piloted and autonomous aircraft, floating radar stations, and long-duration AUV gliders), LEO-15 will be able to expand its reach toward deeper-water shelf areas, further north and south along the shelf, and into shallower water at the outer edge of the surf zone. We hope it will eventually become part of a national and ultimately global network of coastal observatories.

Other LEO systems are planned by Rutgers and WHOI in the Mid-Atlantic Bight, including deeper stations at the edge of the continental shelf and shallower stations offshore Martha's Vineyard (see page 31), and in some of our nation's busiest ports, such as New York and New Jersey. Other universities are implementing LEO-like systems along our coasts and in the Great Lakes. The challenge will be to link this patchwork of local well-sampled systems in a distributed national network that shares regional-scale information.

More information about LEO-15 is available at: marine.rutgers.edu/mrs/LEO15.html.



WHOI's new nearshore observatory on Martha's Vineyard, scheduled to be completed by the fall of 2000, will have land-based and sea-based sensors to continuously monitor oceanic and atmospheric conditions. The observations will be combined via underground and submarine cables at a shore station and available instantaneously on the Internet.

A New Coastal Observatory Is Born

Martha's Vineyard offers scientifically exciting site

James B. Edson, Associate Scientist, **Wade R. McGillis**, Assistant Scientist, and **Thomas C. Austin**, Senior Engineer
Applied Ocean Physics and Engineering Department, WHOI

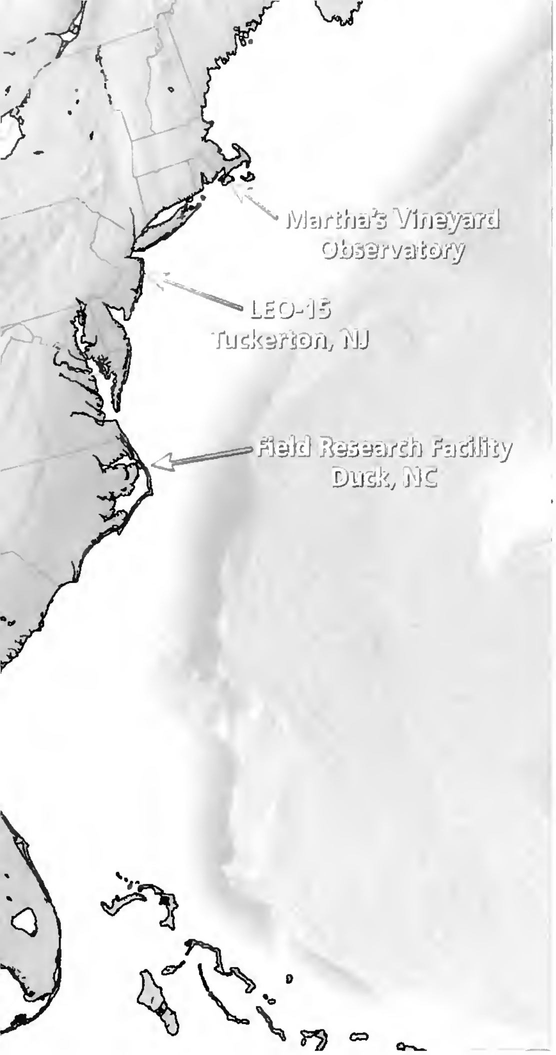
People are not uniformly distributed on our planet. They tend to hug the coastline. An estimated 50 percent of humanity lives within 100 miles of a coastline, and this figure is growing. Here on Cape Cod, we are all keenly aware that the coast is a unique environment that is routinely affected by wave- and storm-driven events. Like most people along the eastern coast of the United States, we know these events often have adverse impacts. We've witnessed beaches eroding more than 10 feet per year. In 1991, even a relatively weak tropical cyclone like Hurricane Bob caused severe damage to New England and North Carolina.

Worldwide, tropical cyclones constitute one of the most important weather forecasting problems. In developing nations, tropical cyclones are the leading cause of death from natural phenomena. A single event took more than 100,000 lives as recently as 1991 in Bangladesh. A year later in the US, Hurricane Andrew killed more than 60 people and caused nearly $30 billion in damage.

Hurricanes, storms, beach erosion, and other natural processes can only exact greater tolls as we turn more of our coastlines into residential and business properties. In addition, a combination of biological, chemical, and physical processes can result in the outbreak of red tides or the dispersal of oil spills or other pollutants along our coastlines. Such events, caused by nature and/or by humans, damage property and natural habitats and harm fisheries, tourism, and the local economies.

Woods Hole scientists and their colleagues have been actively involved in coastal research for many decades. WHOI researcher Alfred Woodcock, for example, discovered in 1948 that red tide outbreaks increased respiratory illnesses in coastal residents because they inhaled contaminated airborne sea spray generated by breaking waves. More recently, WHOI scientists have conducted coastal research at the US Army Corps of Engineers' Field Research Facility (FRF) in Duck, North Carolina, (see page 24) and have helped conceive and build the Long-Term Ecosystem Observatory (LEO-15) off the coast of New Jersey (see page 28).

Interestingly enough, however, WHOI scientists haven't taken full advantage of the coast in their own back yard—primarily for the same reason that they have exploited it as a port for ocean-going research vessels. Martha's Vineyard and the Elizabeth Islands protect Woods Hole and make it a



The combination of the new Martha's Vineyard Observatory, Rutgers University's Long-term Ecosystem Observatory (LEO-15), and the US Army Corps of Engineers' Field Research Facility will provide a valuable network of research installations along the East Coast to study coastal processes.

safe harbor, but they also block scientists from immediate access to undisturbed ocean waves and alongshore currents. In contrast, the southward shoreline of Martha's Vineyard faces the open ocean.Thus, it offers an ideal and still relatively accessible site for studying coastal processes. In fact, its south-facing beachfront is particularly valuable to scientists because prevailing winds blow directly onshore and in line with the direction of the ocean's waves.

With funding from the National Science Foundation, WHOI scientists and engineers have designed a nearshore observatory in the Katama section of Edgartown on Martha's Vineyard. Construction of this observatory began in December 1999 and is scheduled to be completed in time to monitor the fall 2000 hurricane season.

The Martha's Vineyard Observatory will have sensors mounted on two seafloor nodes, at depths of about 5 and 15 meters, respectively, connected to a shore station via a buried cable. Instruments mounted on the nodes will continually monitor mean sea and wave heights, current strengths, seawater turbulence, subsurface sediment movement, sunlight intensity, and the temperature, salinity, and carbon dioxide levels of the ocean's waters. Onshore, a mast extending about 8 meters above the beach's dunes will house meteorological instruments that will sample the near-coast air transported to land by the southerly winds. The onshore instruments will continuously measure wind speed and direction, atmospheric carbon dioxide levels, temperature, humidity, and the concentration of sea salt, water vapor, and small organic or inorganic particles (collectively called aerosols) that are ejected out of the sea and into the air. Measurements made in the atmosphere and the ocean will be jointly collected via underground cables at a shore station in the Katama Air Park, and made available in near real time on the Internet.

Information collected at the Martha's Vineyard Observatory will be combined with data collected at the LEO-15 site off New Jersey and at the FRF in North Carolina. Together, these three facilities will provide a unique network along the East Coast for studying coastal processes (see map, left).

Like FRF and LEO-15, the Martha's Vineyard Observatory will provide scientists with a well-characterized natural laboratory that will enable them to study how winds, waves, currents, seafloor topography and sediment structure, and other factors combine to affect the coastline. In addition, it will enable them to learn about the processes and conditions that affect coastal marine life. However, one of our main objectives for the Martha's Vineyard Observatory is to gain a better understanding of coastal weather phenomena.

Meteorologists are only now beginning to identify and investigate physical processes that are unique to the coastal environment. The same, ever-shifting wind and wave patterns that combine to create such turbulent, dynamic systems at the shoreline and beneath the sea surface, also generate a great deal of action in the air above the sea surface. Winds and waves constantly disrupt the boundary between air and sea, promoting exchanges of gases, particles, heat, and momentum between the ocean and atmosphere.

One of the many outcomes of this lively border exchange is the production of sea spray. Measurements of aerosol concentrations at the Martha's Vineyard Observatory will enable us to learn how sea spray is produced and transported. This, in turn, will help improve our ability to predict marine haze and fog in coastal regions. In addition, we will be able to study how the evaporation of sea spray into the atmosphere affects the transfer of heat and moisture near the ocean surface.

We can also use the observatory to explore how solar energy radiating into the sea surface affects the system. Warmer surface waters, just like warmer air, are more buoyant; thus, warmer waters rise, pushing up air masses above the sea surface, and initiating another series of dynamic processes in the atmosphere.

At the Martha's Vineyard Observatory, we can focus on observing, at a small scale, a range of complex air-sea interactions such as those noted above, which may also take place on a larger scale in the vaster ocean. One high-priority research topic is the study of air-sea exchange of carbon dioxide, a heat-trapping, industrial greenhouse gas that has been accumulating in the earth's atmosphere for the past several decades. Such studies will help us estimate how the oceans absorb and retain this gas, and thus allow us to assess the extent to which the oceans can store excess carbon dioxide, thereby reducing the threat of global climate change.

Many of the studies we propose at the observatory require the expertise of scientists in several disciplines. Carbon dioxide is not the only trace gas

The Martha's Vineyard Observatory will be located on South Beach near the Katama Air Park.

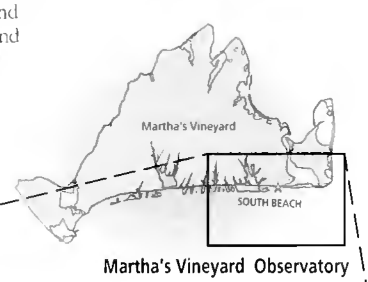
with potentially important biogeochemical consequences. In one scenario, for example, increased sunlight might spark a bloom of phytoplankton that produces an abundance of a gas called dimethylsulfide. Wind and wave action transport dimethylsulfide into the air, where it may create aerosol particles that reflect or block sunlight, possibly cooling the earth's surface and eventually leading to fewer phytoplankton.

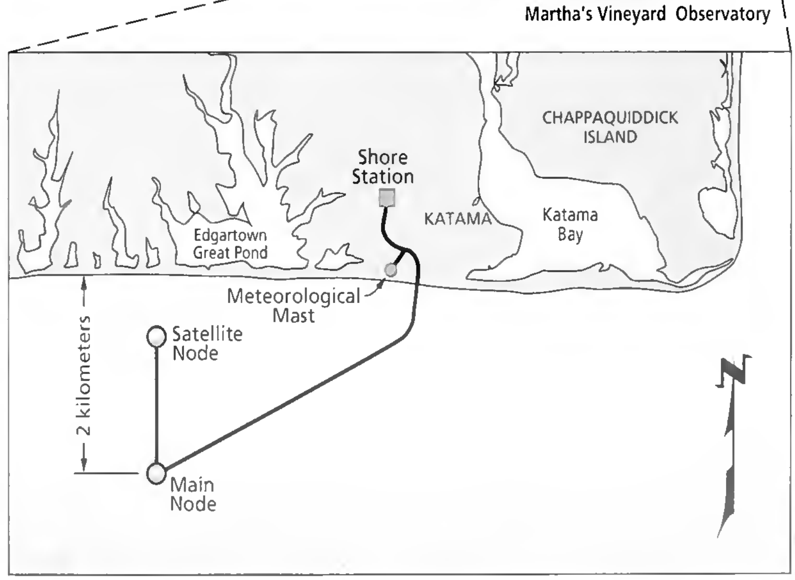
Another area of research that we propose to initiate at the observatory is a study of the interaction between ocean waves and winds during a hurricane event. For example, we could use measurements made at the observatory to prove (or disprove) the theory that winds and waves from hurricanes agitate the ocean like a washing machine, generating foam on the sea surface that acts as a lubricant—thus reducing the drag on the hurricane from the sea surface and possibly keeping it from dissipating faster. Martha's Vineyard's exposure to the open ocean and frequent storms, while hardly a blessing to the island's inhabitants, will provide us with an invaluable means to study the effects of severe storms and possibly hurricanes. The permanent equipment deployed at the facility will include a set of rugged instrumentation able to withstand extremely high wind speeds and rain, allowing measurements that have rarely been collected before, and providing us with the real-time data necessary to improve the computer simulation models that currently predict hurricane events.

As we quickly move toward computer models that couple ocean and atmosphere processes to generate better weather forecasts, we require continuous, long-term, high-resolution measurements of phenomena in the air and water to test and improve these models. Observations from our nascent network of East Coast nearshore observatories and moored ocean buoy observatories represent a first step toward supplying the comprehensive, high-quality data needed to make these coupled models effective. Ultimately, we expect that the improved understanding of coastal processes afforded by the Martha's Vineyard Observatory will be combined within this observational network to improve our abilities to forecast waves, ocean circulation, and weather.

Collaborators on the development of the Martha's Vineyard Observatory include scientists John Trowbridge and Cheryl Ann Butman and engineers Robert Petitt and Jonathan Ware of WHOI's Applied Ocean Physics and Engineering Department (AOPE), and Marga McElroy, Mike Purcell, Roger Stokey, Ben Allen, Ned Forrester, and Robert Goldsborough of the AOPE Ocean Systems Laboratory led by Christopher von Alt.

The Martha's Vineyard Observatory's south-facing beachfront is particularly valuable to scientists because prevailing winds blow directly onshore and in line with the direction of waves.





A long line of glass balls in yellow "hardhats" will provide flotation for a moored buoy observatory in the Pacific Ocean